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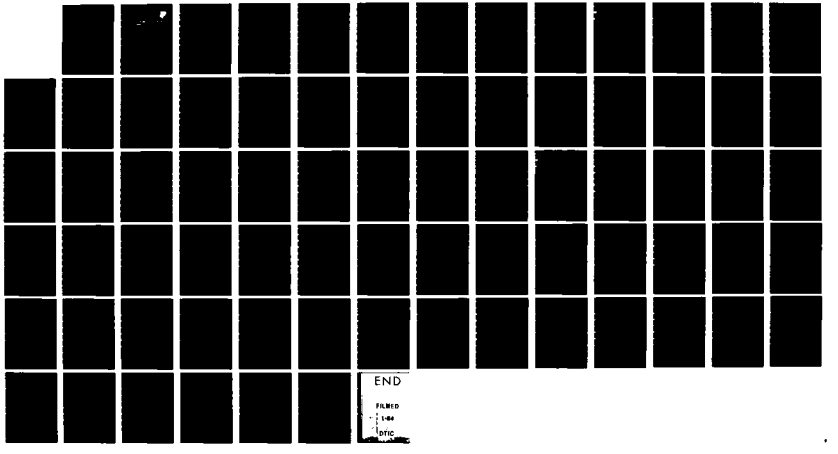

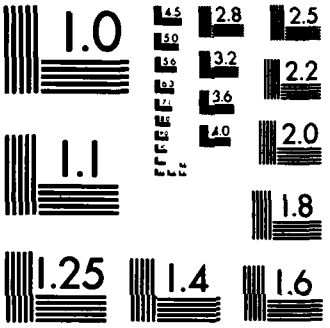

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RADC-TR-83-101
Interim Report
May 1983

INTRASYSTEM ANALYSIS PROGRAM (IAP) CODE SUMMARIES

IIT Research Institute

John J. Dobmeier, Andrew L. S. Drozd and Joseph A. Surace

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(See Reverse)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report contains detailed descriptions and capabilities of the codes that comprise the Intrasystem Analysis Program. The four codes are: Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP), General Electromagnetic Model for the Analysis of Complex Systems (GEMACS), Nonlinear Circuit Analysis Program (NCAP), and Wire Coupling Prediction Models (WIRE).

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IEMCAP is used for computer-aided evaluation of electromagnetic comaptibility (ECM) at all stages of an Air Force system's life cycle, applicable to aircraft, space/missile, and ground-based systems.

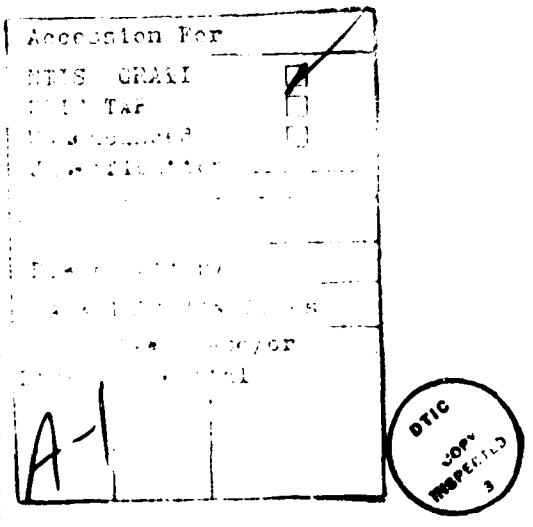
GEMACS utilizes a Method of Moments (MOM) formalism with the Electric Field Integral Equation (EFIE) for the solution of electromagnetic radiation and scattering problems. The code employs both full matrix decomposition and Banded Matrix Iteration solution techniques and is expressly designed for large problems.

NCAP is a circuit analysis code which uses the Volterra approach to solve for the transfer functions and node voltage of weakly nonlinear circuits.

The Wire Programs deal with the Application of Multiconductor Transmission Line Theory to the Prediction of Cable Coupling for specific classes of problems.

Item #19 (Continued)

Method of Moments
Antenna Analysis
Nonlinear Analysis
Volterra Analysis
Cable Coupling



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PREFACE

This document was generated in response to a perceived need to more fully inform the EMC Community of the capabilities extant in the Intrasystem Analysis Program (IAP).

The report was generated in support of the Air Force Systems Command (AFSC) and Rome Air Development Center (RADC) under contract F30602-78-C-0222 titled "EMC/IAP Support Center".

Our sincere thanks are extended to the RADC persons who contributed to this report through several review cycles. In particular we would like to thank Mr. Kenneth Siarkiewicz, Dr. Gerard Capraro, Mr. Jon Valente and Dr. Clayton Paul of the University of Kentucky for their contributions.

SECTION 1.

INTRASYSTEM ELECTROMAGNETIC COMPATIBILITY ANALYSIS PROGRAM

(IEMCAP)

1. The Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP)*

1.1 Introduction

Performance of modern weapons systems is dependent upon the compatible functioning of electrical and electronic subsystems. A typical system includes numerous such subsystems with their associated interconnecting wires and, often, with large numbers of antennas for transmission and reception of required signals. The power and information signals generally occupy a wide range of the electromagnetic spectrum, resulting in the need for carefully designed control measures to confine them within the spatial, spectral, and temporal limits necessary to avoid disruptive interference. Electromagnetic Compatibility (EMC) assurance is thus an integral and crucial part of system and subsystem design engineering. Computerized EMC analysis, as provided by the Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP), is a necessary tool for establishing and maintaining cost-effective interference control throughout the lifetime of a weapon system.

1.2 Code Description and Capabilities

IEMCAP is a systems-level, computerized analysis program which may be used in analyzing electromagnetic compatibility for aircraft, spacecraft/missiles, or ground stations on both present and future systems. It acts as a link between equipment and subsystem EMC performance and total system EMC functionality and provides the means for tailoring EMC requirements to specific systems. This is accomplished in IEMCAP through detailed modeling of the system elements as well as the various mechanisms of electromagnetic transfer to perform the following tasks:

- Provide a database which can be continually maintained and updated to follow system design changes
- Generate EMC specification limits tailored to the specific system
- Evaluate the impact of granting waivers to the tailored specifications
- Survey a system for incompatibilities
- Assess the effect of design changes on system EMC
- Provide comparative analysis results upon which to base EMC tradeoff decisions

* The information provided below has been extracted directly from the following documents: Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP), Volume I, User's Manual Engineering Section, RADC-TR-74-342; Intrasystem Analysis Program (IAP) Model Improvement, RADC-TR-82-20.

The program incorporates state-of-the-art communications and frequency-domain EMC analysis math models into routines which efficiently determine the spectra and evaluate the transfer modes of electromagnetic energy between generators and receptors within the system.

IEMCAP's combined capabilities provide a versatile framework which facilitates modification as the state-of-the-art progresses. This provides a flexibility in updating the program as new or improved mathematical models are developed, and it provides a program which may be easily applied to a wide variety of EMC analysis and design problems by utilization of only the necessary modules for the specific problem.

The system model for IEMCAP employs the standard EMC approach of identifying all ports in the system having potential for undesired signal coupling. These ports are divided into arrays of emitter ports and receptor ports having identifiable coupling paths.

All emitters in a system are characterized by emission spectra and all receptors are characterized by a susceptibility spectra. All ports and coupling media are assumed to have linear characteristics. Emissions from the various emitter ports are assumed to be statistically independent so that signals from several emitters impinging at a receptor port combine on an RMS or average power basis. Other waveform parameters that receptor ports are sensitive to include total energy (total energy susceptibility) and peak current (or voltage) and rise time (peak sensitivity considerations for digital-type devices susceptible to instantaneous waveform levels). These latter sensitivity considerations are currently being anticipated for future inclusion into IEMCAP.

Emitter and receptor ports may be intentional or unintentional. An example of an unintentional port is leakage into or out of an equipment case. An example of an intentional port is a connector pin through which AC power, signals, etc. are brought into or out of the equipment. Such ports are connected to wires or antennas.

All intentional ports must generate and/or receive certain types of signals to perform their intended function. The signals or responses which are intentionally generated and coupled from port-to-port are called operationally required and cannot be altered without affecting system operation. In addition to the required signals, there may be additional undesired outputs and/or responses. These are called operationally non-required. For example, an emitter can have non-required outputs in the form of harmonics, and a receptor can have an undesired response in the form of an image response. It should be noted that unrequired responses may be produced both by unrequired signals and/or by required signals which are unintentionally coupled to the wrong ports.

For each emitter port, a two-component spectrum represents the power levels produced over the frequency range. The broadband component represents continuous emissions, which varies slowly with respect to frequency; while the narrowband component represents discrete emissions, which varies rapidly with respect to frequency. The broadband components are in units of power spectral density, and the narrowband are in units of power.

For receptors, a spectrum representing the susceptibility threshold over the frequency range is determined. The susceptibility level is defined as the minimum received signal which will produce a desired response at a given frequency.

For each intentional port, a portion of the frequency range is defined as the required range. All signals within this range are required and cannot be adjusted. Outside this range limits may be set for the maximum emission and minimum susceptibility levels. Within the required range, the spectrum is defined by a mathematical model of signal level versus frequency. This can be either from equations of the frequency domain representation of the signal or directly from a user-defined spectrum. Outside the required range, military standard levels are used for the port spectra. During specification generation, if these assumed spectrum levels cause interference, they are adjusted such that there is compatibility. By adjusting the spectra of emitters and receptors for compatibility, the maximum non-required emission an minimum susceptibility levels are obtained which will produce a compat e system. To prevent too stringent specifications from being gene ed, each spectrum has an adjustment limit.

While any values could be used for the initial non-requi pectra, IEMCAP uses the limits of military EMC specifications MIL- 61A and MIL-I-6181D (MIL-I-6181D has been superseded by 461A which has been superseded by 461B). The initial levels may be relaxed or tightened from these if desired. from these if desired.

The general approach in performing the analysis tasks is two-fold. First an emitter-receptor port pair is selected and their type, connection, wire routing, etc. are quickly examined to determine if a coupling path exists. If a path exists the received signal is computed at the receptor and compared to the susceptibility level. In addition to the emitter-receptor and port pair analysis, the program also computes the total signal from all emitters simultaneously coupled into each receptor.

In conjunction with the above process, IEMCAP uses a sampled spectrum technique in which each spectrum amplitude is sampled at various frequencies chosen by the program and/or by the user across the range of interest. Considering the requirement of MIL-STD-461A of 3 frequencies per octave from 30 Hz to 18 GHz, this requires approximately 90 sample frequencies. To avoid missing narrow peaks between sample frequencies, IEMCAP samples the spectrum in the interval half-way between the sample frequency and each of its neighboring sample frequencies. For emission spectra, the maximum level in the interval is selected and assigned to the sample frequency in the interval and for susceptibility spectra the minimum level is selected and also assigned to the sample frequency in the interval. This effectively quantizes the spectra with respect to the sample frequencies.

The range of frequencies covered by the analysis is governed by the user. The program will presently accept any range from 30 Hz to 18 GHz, but if desired, the user may concentrate all 90 frequencies over a smaller interval within this range. These frequencies are applied to a given equipment which contains emitter and/or receptor ports.

Based on the defined conditions and overall analysis approach, an electromagnetic interference margin (EMI) is calculated. An incompatibility is said to exist when sufficient signal from an emitter port, or ports, is unintentionally coupled to a receptor port to exceed its susceptibility threshold.

EMI margins of value greater than OdB indicate interference. Values less than OdB indicate either compatibility or interference. Currently, IEMCAP spectrum models and transfer coupling models represent a "worst-case" approach to systems analysis and prediction of EMC/EMI. Although uncertainty exists as to whether compatibility or interference actually occurs aboard a given system in accordance with the worst-case philosophy of IEMCAP, a minimization of the uncertainty has been considered in the selection of interference margins included in IEMCAP.

A new port spectra algorithm is currently being considered to replace the quantization method in IEMCAP for modeling emitter and receptor spectra. Basically, this new model reduces to a requirement for an automated generation all frequencies and corresponding amplitudes for defining the port spectra of an equipment. The generation of the equipment frequency table is accomplished by determining the required frequencies from prestored models, harmonics, non-required frequencies from appropriate MIL-STDs and user-specified frequencies from IEMCAP input data. The port spectra amplitudes are computed from prestored emission and susceptibility models, harmonics, user-specified data, and prestored MIL-STD levels. Also, the frequency range for analysis is expected to extend from 0 to 50 GHz and greater. Currently however, the 30 to 18 GHz limitation is imposed on each port, which is categorized by function into one of six types (RF, Signal, Control, Power, EED, Case); each type has its own sub-interval of frequencies within the overall range as adapted from MIL-STD-461/462. The non-required spectrum model routines will generate zero emission and susceptibility outside these sub-intervals.

A number of important system-level EMI problems result from nonlinear effects in emitters and receptors. At the present time, however, the IEMCAP considers only interference caused by power transferred linearly from emitter to receptor. To accurately predict all instances of possible EMI, IEMCAP will ultimately be expanded to include interference due to the following nonlinear effects, which are recognized to cause system performance degradation:

1) Receiver Intermodulation

2) Spurious Responses

3) Cross Modulation

4) Desensitization

5) Gain Compression and Gain Expansion

IEMCAP (currently in release 05) is designed for use by an EMC systems engineer with a minimum of computer experience. The input data requirements, program control, and output formats are easily learned and

engineering oriented. The input data is directly obtainable from system and subsystem operational specifications or measured data.

To organize the input data into a form convenient for collection and utilization by the user and the program, a hierarchy structure is defined. The system is divided into subsystems which are groups of equipments performing related tasks. For example, an aircraft system might have a navigation subsystem which is composed of several equipments such as a transmitter-receiver unit, a display unit, and a navigation computer. The physical boxes comprising the subsystem are defined as equipments, and electromagnetic energy may enter or leave these equipments via ports.

The system data defines the system type, overall physical dimensions, coordinate system parameters, and basic analysis parameters applying to the entire system. It also includes common model parameter tables. These tables contain basic parameters for apertures, antennas, filters, and wire characteristics which have multiple use throughout the system.

The subsystem data is organized into a heiarchy which is summarized below:

Subsystem - A subsystem consists of well defined parts of a system usually performing a related task. A radar package and a central computer complex are examples of subsystems. This level is defined for convenience in organizing the data and is not a functional level within the program. Hence, equipments need not be specified with reference to a subsystem.

Equipment - An equipment is a physical box mounted in the system, such as a transmitter unit.

Port - A port is a point of entry or-exit of electromagnetic energy from an equipment. A port may be connected to an antenna or to a wire. Leakage into and out of the equipment case is also a port. A port may be designated as a source (emitter) a receptor, or both. The analyses are performed on a port-to-port basis. All ports within the same equipment are assumed compatible with each other.

Source - A source is a port which emits electromagnetic energy.

Receptor - A receptor is a port which is susceptible to electromagnetic energy.

Wire bundle data may also be considered next and organized into a heirarchy, which allows complex wire routings to be analyzed. The components are as follows:

Bundle - A bundle is a group of wires which, for some portion of their lengths, run parallel to each other.

Bundle Point - A point in the system at which a bundle branches or changes direction. Between points wires are assumed to run in straight lines, and no branching occurs.

Segment - A segment is a section of a bundle running between points. Segments are designated by giving the bundle points. Within a segment the wires are assumed to run parallel. A segment may also run , a dielectric aperture and be exposed to energy from external antennas and environmental electromagnetic fields.

Wire - A wire connects two or more ports. Its routing is specified by designating the bundle points through which it passes for which segments have been defined. Care must be taken that a wire routing not close on itself or an error will result. The wire physical parameters are given by referencing the Wire Characteristics Table, which is specified at the system level.

All user program control and data inputs to the program are on punch cards or card images and are in free-field format. Basically, the inputs are in the form of statements in which the parameters may be entered into any columns on the cards (card images). The basic format requires a keyword which identifies the type of data, an equals sign, and the relevant parameters separated by commas. The parameters and subparameters on these cards must be in a prescribed order and may represent numerics, alphabetic codes, or alphanumeric designations.

During execution, a number of printed outputs are generated by IEMCAP. If errors are found in the data during the input decode process, an appropriate error message is printed along with the data card that is in error (preprocessor error checking); additional error messages are printed during initial processing if errors are detected during file updating, generation of initial spectra, or wire-routing descriptions (post-processing error checking).

After all input data has been read, decoded, and checked for errors, a listing of the input is provided. Also, during initial processing, a report of all the data that comprises the system for which the analysis task is to be performed is printed. This comprises the Intrasystem Signature File (ISF) report consisting of a summary of the system, subsystem, and equipment data, followed by each equipment's frequency table and initial port spectra of each port in the equipment and, lastly, the bundle data.

Supplemental and debug output can also be requested which produces output useful for following the logic in the wire-mapping routines via printing of internal flags and messages to aid in software maintenance. The supplemental printout of the wire mapping routines follows the normal bundle data output.

IEMCAP consists of two sections which are executed separately. The Initial Decode and Initial Processing Routine (IDIPR) reads, validates, and decodes user input; manages and assembles the data for analysis; generates the initial port spectra; and writes this data on permanent and working data storage files. The second section, the Task Analysis Routine (TART) uses this data and the transfer models to perform Baseline Survey, Trade-off Analyses, Waiver Analyses, and Specification Generation.

The TART Baseline Survey outputs are summaries of transfer ratios, received signal power at receptors, and EMI margins between emitter-receptor port pairs and considers the total received signal from all emitters into each receptor. The margins are printed for each frequency, and an integrated margin is also printed which represents the cumulative effect of coupling across the entire frequency range of interest.

The Trade-off and Waiver Analysis outputs are similar to those of the Baseline Survey; these outputs illustrate the before and after effects of modifying system elements or shifting portions of the emitter and/or receptor spectra, respectively.

For Specification Generation (SGR) runs, the output format is also similar to the Baseline Survey summary with the addition of emitter spectrum adjustment, receptor spectrum adjustment, unresolved interference, and final adjusted spectrum summaries. These summaries represent adjustments made to the initial non-required emission and/or susceptibility spectra such that the system becomes compatible. The amount of adjustment is controlled by user inputs.

Supplemental outputs for any of the above analysis options may be obtained if requested. These additional outputs consist of antenna coupling propagation path factors involved in computing path loss (antenna-to-antenna), components of the transfer ratio involving coupling through apertures exposing receptor wires (antenna-to-wire), and capacitive and inductive coupling components per frequency (wire-to-wire).

The amount of standard output can be limited by special output control features such as an EMI margin printout limit value and/or port-supress commands which inhibit the output on ports that are not of interest.

The mathematical models used by the program can be divided into the general classifications of emitter models, receptor models, transfer models, and the system model. The emitter models relate the parameters of the equipment and port data to the power spectral density output by the emitter port. These emitter models are incorporated in the program for most common emitter types and provision is made for user input of spectral densities for those types not modeled. The transfer models are used to compute the ratio between the power output at an emitter port and that present at the input to a receptor port.

Receiver models relate the power spectrum at the receptor port to the response produced by that spectrum. This calculation is based on the sensitivity of the receptor versus frequency.

The system model is used to relate the manner in which the emitter, transfer and receptor models are combined to account for simultaneous operation of all equipments. This enables calculations for compatibility and specification generation to be performed not only between pairs of equipments, but also among all equipments when operating simultaneously.

IEMCAP determines if a coupling path exists between two ports. If a path exists, the appropriate transfer model routines are used to compute the transfer ratio of all frequencies of interest. The models consist of:

- o Antenna-Coupled Transfer - This includes antenna-to-antenna and antenna-to-wire coupling on an aircraft (winged vehicle), a spacecraft (wingless vehicle), and over ground. Antenna models and shading (diffraction) models for propagation around wings and fuselage are included.

- o Wire-to-Wire Transfer - These routines compute coupling within a wire bundle. Transfer models between open, shielded, and double shielded wires with both balanced and unbalanced configurations are included.

- o Case-to-Case Transfer - This model computes coupling resulting from electromagnetic leakage from equipment cases.

- o Filter Models - These routines compute losses due to filters between the emitter and receptor ports and the coupling medium. Models for single tuned stage, Butterworth, low-pass, and band reject filters are included.

- o Environmental Field Models - These routines compute the if present, to receptor ports.

In the antenna model, antennas are categorized into two groups. Antennas included in the first group are low gain antenna types such as a monopole, dipole, slot or loop. Antennas included in the second group are medium-to-high gain antenna types, such as horn or parabolic reflector.

All antennas in the first group are modeled analytically by trigonometric expressions. A dipole, for example. has a directive gain = 1.6 sin θ, where θ is the angle of an arbitrary direction with respect to the dipole axis.

All antennas in the second group are modeled by a three dimensional three-sector representation. Each sector subtends a solid angle in the unit sphere and has an associated quantized antenna gain.

The three sectors are intended to correspond to a main beam, major sidelobe and backlobe.

Since antenna measurements are rarely available at frequencies other then the design frequency or the first few harmonics thereof, the representation is considered frequency independent.

The gain in an arbitrary direction θ, ϕ in the coordinate system of the antenna is found by determining the sector in which that direction falls and choosing the gain associated with that particular sector.

For the simplified theoretical Ground Wave Antenna-Coupling Model, a smooth earth surface is assumed, with a 4/3 earth radius accounting for atmospheric refraction. The model is valid for frequencies greater than 1

MHz and less than 1 GHz, and moderate antenna height. The limitation on antenna height is a consequence of a plane earth approximation for distances up to:

$$d = \frac{h_1 \ h_2}{79.6\lambda}$$

where h_1, h_2 = antenna heights in meters and λ is the wavelength in meters. The plane earth approximation makes possible a two-ray optics solution, neglecting the "surface" wave for the moment. The simplified theoretical ground wave model is slightly modified to include the effect of the surface wave.

The Intravehicular Antenna-Propagation Model calculates the propagation loss associated with an electromagnetic coupling path when both source and receptor are located on the same aircraft or spacecraft. The power received is related to the power transmitted in the following way:

$$P_R = P_T + TFS + SF$$

where

P_T=transmitter power (dBm)

TFS=free-space transmission factor (dB)

SF=shading factor (dB)

The free-space transmission factor is derived from the Friis transmission equation and is given by:

$$TFS = G_T + G_R + 20 \ Log_{10} \left(\frac{\lambda}{4\pi D}\right)$$

where

G_T=gain of transmitting antenna (dB)

G_R=gain of receiving antenna (dB)

λ =wavelength (meters)

D = distance between two antenna (meters)

Near field conditions are considered where 0-dB transfer gain is assumed for antenna separations which are less than the maximum dimension of the transmitter and receiver antenna. Far field calculations are based

on whether the minimum antenna distance exceeds the maximum of 3λ (for wire type antennas) or $\frac{2D^2}{\lambda}$ (for surface type antennas).

Where a portion of the propagation path is around any curved surface, allowance must be made for shading effects. An equation for the fuselage shading, as a portion of the shading factor SF was derived from Hasserjain and Ishimaru. When a portion of the propagation path is around the wing, or any surface edge, allowance must be made for diffraction effects. The total shading factor is then the sum of the edge and cylindrical surface factors. Appropriate tangent points relative to the vehicle are considered for various antenna placement configurations during the determination of these shading effects.

During the calculation of wire-to-wire coupling, a check is made to determine if the wires are in the same bundle and have a common run length. If these conditions are met, the wire-to-wire coupling routine is called. This routine computes the spectral voltages induced in the receptor circuit by the emitter circuit. These calculations are performed on a pair basis (only one emitter circuit considered to couple with the receptor circuit for each calculation) with the effects of all other circuits neglected during this calculation. Each possible pair coupling is computed in turn and the total coupling is caluclated by summing all of the pair couplings without regard to phase. It should be noted that the validity of this wire-to-wire coupling model has been verified by experimental data.

In order to make this applicable to general systems, it is necessary to have models available for computing the coupling between the circuit pairs even when the connecting wires have a relatively complex configuration (such as shielded, twisted pairs). For this program, the circuits for which models have been developed include:

(a) Single (unshielded) wires with ground return

(b) Twisted pair circuits (balanced or unbalanced)

(c) Shielded wires (single or double shield) with single or multiply grounded shields

(d) Shielded twisted pair circuits (balanced or unbalanced, single or double shield) with single or multiply grounded shields.

These models are valid for both emitter and receptor circuits and any type of emitter circuit may be analyzed with any type receptor circuit.

For frequencies where the wire length is short compared to a wavelength, the models provide an accurate representation of the actual coupling situations. However, for the frequencies where the wire lengths are comparable to or greater than the wavelength, the models approximate the envelope of the coupling curve so that the predicted coupling is never less than the actual.

The basic model for wire to wire coupling considers capacitive

coupling due to the interwire capacitance and inductive coupling due to the mutual inductance between the wires. This model uses the approximation that the total coupling can be computed as the sum of the capacitive and inductive coupling computed separately.

The analysis of circuits which are more complex than a single wire with ground return is accomplished by using an equivalent single wire representation for the circuit. Although the single wire equivalents for these circuits are different for capacitive and inductive coupling, this technique allows the same routines to be used for all circuits considered.

The calculation procedure is modified somewhat for emitter and receptor circuits which have several branches, discontinuities, pigtail shield terminations, etc. This is necessary because the emitter current and equivalent circuit change from segment to segment for circuits with these discontinuities. In this case the emitter current (and the summation of voltages coupled to the receptor port) is computed on the basis of the entire emitter (receptor) configuration but the coupling is computed on a segment by segment basis. This is accomplished by first computing the current and the single wire equivalent for each segment of the emitter circuit which has a common segment with the receptor port circuit. The proper equivalent receptor circuit segment is paired with the correct emitter segment for computation of the coupling on a segment by segment basis. All of the coupling components are then summed to determine the total coupling. This is done for both capacitive and inductive coupling at all frequencies for which the coupling is required.

This method of segmenting the wires allows the calculation of the effects of environmental fields on the complete receptor circuit at the same time the first emitter circuit is being analyzed. This is accomplished by using asymptotic expressions for field to wire coupling on internal circuits.

In all parameter calculations, the wire spacing is taken as one-forth of a bundle diameter. This value was picked as a reasonable compromise between the worst case situation (where wires are separated only by their insulation) and the average value of separation of wires in a bundle (assuming random placement of wires during bundle construction).

The case-to-case model uses the emission and susceptibility levels according to MIL-STD-461A or MIL-STD-6181D. These levels are related to the system configuration by modeling each case as though it were a dipole. The source model assumes a $(1/r)^3$ fall off for both the electric and magnetic fields.

The filter models represented in IEMCAP are ideal, lossless networks, made up of only reactive elements (capacitors and inductors).

The filter transfer models calculate the "insertion loss" in dB provided by a filter at a given frequency, i.e., the reduction in delivered power due to insertion of a filter. Thus the insertion loss of the single tuned filter at the resonant frequency is 0 dB, i.e., the insertion of the filter does not attenuate the signal delivered to the load at that frequency.

Practical filters are not ideal, lossless networks; there are always dissipative elements which affect filter performance. Consequently the filter models provide for a minimum insertion loss to represent actual dissipation at the tuned frequency or in the pass band. The filter models also provide a maximum insertion loss or isolation to represent the departure from the ideal rejection in the rejection band. The minimum and maximum insertion loss provide lower and upper bounds for the filter transfer function.

The coupling from environmental electromagnetic fields onto wiring is important in the design of USAF systems. Usually, the fields enter the vehicle through dielectric apertures in the systems skin and couple onto wires immediately adjacent. These apertures include radomes, canopies, landing gear doors, camera windows and air intakes, on aircraft and space vehicles and doors and windows in ground systems.

Exposed wires are assumed to be adjacent to the aperture, and the amount of RF energy coupled depends on the aperture size and location. A transmission line model is then used to compute the currents induced in the wire loads. Worst-case electromagnetic field vector orientation is determined and used for the calculation.

A number of IEMCAP applications have been cited and noted below. The following platforms (aircraft and spacecraft) have been modeled:

S-3A
F-15
DSCS-III
F-18
F-14
F-16
A-10
A-7D
F-111
F-105
RF-4C
F-4
B-52
EC-135
SCATHA
IUS
PLSS
OV-10

1.3 Software Considerations

As discussed above, IEMCAP is divided into two sections, and the basic flow through them is shown in Figure 1. These sections are executed independently with intermediate data storage on a number of disk or tape files known as working files. Depending on the analysis and the size of the system being analyzed, the program sections can be executed in succession or run separately. For small systems or a small number of updates, the first setup would probably be used. However, for a large system the first section can be run independently until data errors have

been eliminated, at which time the second section would be run.

The first section of IEMCAP is the IDIPR module which consists of four basic subprograms. The four subprograms are the Input Decode Routine (IPDCOD), Initial Processing Routine (IPR), Spectrum Model Routines (SPCMDL), and the Wire Map Routine (WMR).

The second section of IEMCAP, TART, uses the data compiled by IDIPR to perform the desired analysis task. This consists of one of the four tasks summarized below:

- o Specification Generation - Adjusts the initial non-required emission and susceptibility spectra such that the system is compatible, where possible. The user-specified adjustment limit prevents too stringent adjustments. A summary of interference situations not controlled by EMC specifications is printed. The adjusted spectra are the maximum emission and minimum susceptibility specifications for use in EMC tests.

- o Baseline System EMC Survey - Surveys the system for interference. If the maximum of the EMI margins over the frequency range for a coupled emitter-receptor port pair exceeds the user-specified printout limit, a summary of the interference is printed. Total received signal into each receptor from all emitters is also printed.

- o Trade-off Analysis - Compares the interference for a modified system to that from a previous specification generation or survey run. The effect on interference of antenna changes, filter changes, spectrum parameter changes, wire changes, etc. can be assessed from this.

- o Specification Waiver Analysis - Shifts portions of specific port spectra as specified and compares the resulting interference to that from a previous specification generation or survey run. From this the effect of granting waivers for specific ports can be assessed.

TART is composed of two basic routines. The Specification Generation Routine (SGR) performs the first task above, and the Comparative EMI Analysis Routine (CEAR) performs the remaining three. These interface with the coupling math model routines to compute the transfer ratios between emitter and receptor ports.

The two parts of IEMCAP are executed separately with data files used for intermediate storage between parts. Computer resources used are illustrated in Figure 1.

Central Processing Unit (CPU) core memory to load and execute each part of IEMCAP on a Honeywell 6180 using the Fortran J compiler are as follows:

IDIPR - 91K words (decimal)
TART - 81K words (decimal)

The files are categorized as permanent, working and scratch. Permanent files are used to store data and analysis results for use in subsequent runs. Working or intermediate files provide temporary storage for the data in a form for efficient use by the various routines. They also provide intermediate data storage between IDIPR and TART. Scratch files are used for temporary storage within IDIPR and TART.

A typical aircraft, spacecraft, or ground system can contain thousands of ports. If every emitter port had to be analyzed in conjunction with every receptor port, the run time, core memory size, and file storage would be extremely large. Therefore, the maximum system size shown in Table 1 was established. For each equipment, the 15 ports include the required case leakage, and, therefore, 14 intentional ports are allowed.

The amount of file space necessary depends on the size of the system being analyzed. The execution time also depends on the system size. IDIPR time is approximately 0.1 second per input card. TART run time primarily depends on the number of coupled port pairs. This potentially increases as the square of the number of ports. In general though, each emitter port will not be coupled to each receptor port so the actual time will be less. Also, the TART time depends on the analysis task. Specification generation requires three passes through the emitters per receptor with two passes through the receptors per run and hence runs longer than the other tasks. Table 2 gives the run times and file sizes for two test cases run on the CDC 6600.

Table 1

MAXIMUM SYSTEM SIZE	
EQUIPMENTS	40
PORTS PER EQUIPMENT	15
TOTAL PORTS (40 x 15)	600
APERTURES	10
ANTENNAS	50
FILTERS	20
WIRE BUNDLES	140
TOTAL NO. OF WIRES	280
SEGMENTS PER BUNDLE	140
BUNDLE POINTS PER WIRE	11

Furthermore, IEMCAP is a self-contained ANSI Standard Fortran program which consists of approximately 16K lines of code (approximately 8K each per module). It has successfully been installed on the following computer systems:

CDC/CDC CYBER
IBM
VAX

UNIVAC
HONEYWELL
PDP
XEROX
AMDAHL

1.4 Source

The IEMCAP program was developed and written by the McDonnell Aircraft Company, St. Louis, Missouri for Rome Air Development Center (RADC/RBCT), Griffiss Air Force Base, New York. The program and required documentation were released in 1974 and are currently maintained by the EMC/IAP Support Center at Griffiss Air Force Base, operated by IIT Research Institute, and sponsored by RADC. The program can be obtained from the Support Center along with supplementary products and services as required.

Since the establishment of the EMC/IAP Support Center, the number of IEMCAP users has increased dramatically. User feedback has helped in guiding the efforts of the Center in updating, maintaining, and developing new software models and enhancements to IEMCAP. The following IEMCAP users which represent government, industry, and academia have been recognized:

ADTC/ADDSU
AEROJET ELECTRO SYSTEMS
AEROSPACE CORPORATION
AFAL/TEA-4
APPLIED TECHNOLOGY
ASD/ENAMA
ATLANTIC RESEARCH CORPORATION
AVCO SYSTEMS DIVISION
BALL AEROSPACE
BBC BROWN BOVERI AND COMPANY LTD
BELL AEROSPACE TEXTRON
BELL HELICOPTER COMPANY
BENDIX ENERGY CONTROLS DIVISION
BOEING COMPANY
BRITISH AEROSPACE DYNAMICS
BRITISH DEFENSE STAFF
CONTROL DATA CORPORATION
DEFENSE RESEARCH ESTABLISHMENT
DEPARTMENT OF COMMERCE
EATON CORPORATION
ECAC/XM
ESD/TOET
FAIRCHILD SPACE & ELECTRONICS
GENERAL DYNAMICS CORPORATION
GENERAL ELECTRIC COMPANY
GEORGIA INSTITUTE OF TECHNOLOGY
GRUMMAN AEROSPACE
GTE SYLVANIA
HARRIS CORPORATION
HUGHES AIRCRAFT COMPANY
IIT RESEARCH INSTITUTE

IRT CORPORATION
ISRAEL A/C COMPANY
JET PROPULSION LAB
LOCKHEED CORPORATION
LOCKHEED MISSILE & SPACE COMPANY
LOCKHEED-GEORGIA COMPANY
EATON CORPORATION
GEC-MARCONI ELECTRONICS LTD
HOKUTO TRADING COMPANY INC
IBM CORPORATION
ITALIAN AEROSPACE INDUSTRIES
JOHN DEERE
LORAL ELECTRONICS
MARTIN MARIETTA AEROSPACE
MCDONNELL DOUGLAS CORPORATION
NAVAL AIR DEVELOPMENT CENTER
NAVAL AIR SYSTEMS COMMAND
NAVAL ORDNANCE STATION
NAVAL RESEARCH LAB
NAVAL SURFACE WEAPONS CENTER
NAVAL WEAPONS CENTER
NORTHROP CORPORATION
NAVAL POST GRADUATE SCHOOL
PACIFIC MISSILE TEST CENTER
PACKARD ELECTRIC
RCA CORPORATION
ROCKWELL INTERNATIONAL CORPORATION
SANDERS ASSOCIATES
SANDIA LABS
SIKORSKY AIRCRAFT
SOUTHWEST RESEARCH INSTITUTE
SPERRY UNIVAC
SYSTEMATICS GENERAL CORPORATION
TEXAS INSTRUMENTS
TRW SYSTEMS GROUP
US ARMY CORADCOM
USACEEIA/CCC-EMEO-ECD
WESTERN ELECTRIC COMPANY INC
WESTINGHOUSE ELECTRIC
WESTLAND HELICOPTERS LTD
WSMC-SEM

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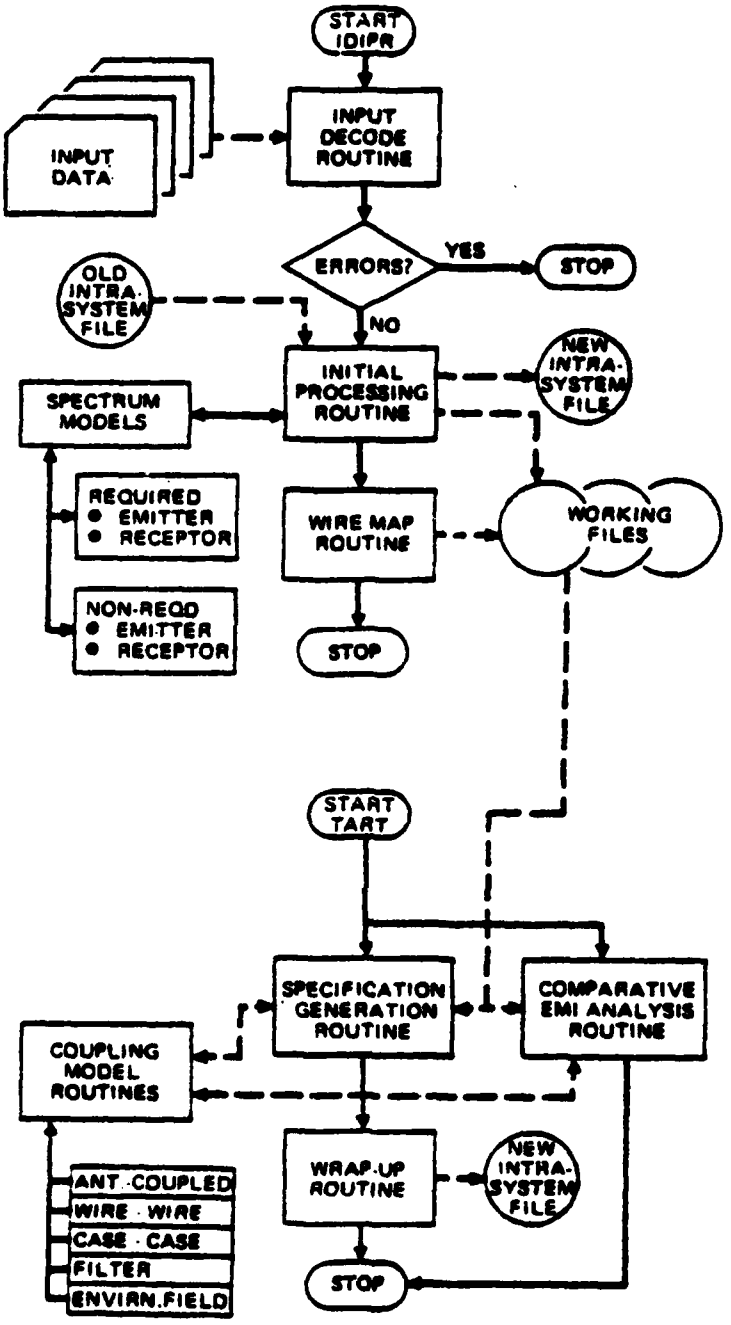

FIGURE 1
IEMCAP FUNCTIONAL FLOW

TABLE 2

EXECUTION TIMES AND SIZE OF PERMANENT AND WORK FILES FOR SAMPLE RUNS

	TEST CASE 1	TEST CASE 2
DATA CASE SIZE		
Total No. Cards Input to IDIPR	170	241
Total No. Ports	33	56
EXECUTION TIMES		
Execution time IDIPR	17.4 sec	24.5 sec
Execution time TART-SGR	176 sec	186 sec
FILE SIZE IN WORDS (Decimal) (Necessary Files)		
New ISF	10,862	16,000
Baseline Transfer File	35,000	41,000
Emitter Spectrum	3,012	4,200
Receptor	1,792	2,670
Emitter Equipment	1,634	2,350
Receptor Equipment	1,631	2,380
Wire Bundle	97	400
Wire Map	640	2,390
Array	183	300
Processed Input File	3,000	4,200

SECTION 2.

GENERAL ELECTROMAGNETIC MODEL FOR THE ANALYSIS OF COMPLEX SYSTEMS

(GEMACS)

2. The General Electromagnetic Model for the Analysis of Complex Systems (GEMACS)*

2.1 Introduction

The GEMACS code is the result of an effort to develop engineering tools to support the electromagnetic (EM) fields analysis required during the design, development, fabrication, installation, maintenance and modification of electrically complex systems.

GEMACS employs the Method of Moments (MOM) technique to solve Maxwell's equations for an arbitrary geometry of radiators and scatterers. It has two major advantages over other MOM codes. First, it enables the user to specify a system with up to 2000 unknowns, instead of 200 to 300. (Relatively small structures requiring approximately 100 unknowns can be solved efficiently using standard modeling techniques). Out-of-core manipulation and banded matrix iteration (BMI) are the major features of this code which make the solution of such large systems of equations practical.

Secondly, the input language for the code, as well as the architecture and structure of the code itself, are designed to permit an organized growth of the capability of the code. A basic function of the kernel of the code involves the storage and manipulation of large quantities of data. These capabilities have been utilized to solve the EM fields analysis equations in either of two ways. It is the intent of the code design to allow the incorporation of other solution techniques, such as Bodies of Revolution (BOR) and the Geometrical Theory of Diffraction (GTD).

The program provides the short-term capability to model and characterize large systems in terms of near/far-field radiation patterns and scattering cross-section, predict the coupling between large numbers of collocated antennas and the input impedance of antennas in large radiating systems. The long-term advantage is the inherent growth potential and Air Force wide commonality available to the users of this code.

2.2 Code Description and Capabilities

GEMACS is a highly user-oriented general purpose code designed for an analysis of a variety of complex electromagnetic problems. The user is assumed to be an experienced electromagnetics analyst with a fair understanding of applied linear algebra. The current version (release 3) of the code supports all of the functions necessary for using one thin-wire and one surface patch (Method of Moments) formalism. The GEMACS code uses a high-level language and provides flexibility of control over the computational sequence by the user. Error messages, debug and trace options, and other features are included to aid the user in identifying sources of fatal errors.

* The description which follows was extracted directly from the following documents: An Introduction to the General Electromagnetic Model for the Analysis of Complex Systems (GEMACS), RADC-TR-78-181; and the General Electromagnetic Model for the Analysis of Complex Systems, RADC-TR-77-137, Volumns I-II.

One MOM formalism used in the present code includes the thin-wire Pocklington integral equation, pulse plus sine plus cosine expansion functions, point matching, and a charge redistribution scheme at multiple wire junctions. The GEMACS code includes most of the engineering features of the other codes such as loading and ground plane effects. However, the range of applicability of the moments technique is extended to objects of larger electrical size in the GEMACS code by using a solution method for linear simultaneous equations called BMI (Banded Matrix Iteration). The user must have a limited understanding of the solution method to insure convergence and reasonable efficiency.

The thin-wire MOM approach can be used to solve general physical problems involving actual wires, wire grid models of conducting surfaces, or a combination of these. Wire grid modeling is not yet a highly defined process. Modeling guidelines developed in recent studies are documented. The user must reduce the physical problem to a thin-wire model. The GEMACS code includes a highly flexible geometry processor to aid in this task. The user specifies the frequency, additional features such as loading or the presence of a ground plane, and the excitation. Excitation options currently include plane or spherical waves, voltage sources for antennas, or arbitrary excitations on specified individual wire segments. Load options currently include fixed (as a function of frequency) lumped loads, series or parallel RLC networks, and finite segment conductivity.

A second MOM formalism is the use of the Magnetic Field Integral Equation (MFIE). Here the surface current is expanded in a set of pulse expansion functions, except in the region of a wire connection. Two orthogonal current directions are assumed for each surface patch. Point matching is used at the patch centers. In the region of a wire connection to a patch, four subpatches are internally generated, and the continuity of current equation at the center of the patch takes into account the singular component due to the current flowing from the wire onto the surface. This provides a viable alternative to the wire grid modeling approach for a surface.

GEMACS can also use the physical symmetry of the structure to decrease matrix fill time and matrix equation solution time. The symmetry may be either planar or rotational. Since only the physical symmetry is used, no restriction is placed on the excitation or loading of the structure regarding symmetry.

The code generates a set of linear simultaneous equations from the information provided. The user controls the process by which the equations are solved. If the total number of wire segments in the model is sufficiently small, standard solution methods are efficient. Solution by full matrix triangular decomposition, in which the Gauss-Jordan algorithm is used, is one of the least expensive general methods and is supported by GEMACS. For large problems this method is too expensive, and the BMI solution method should be specified by the user. This method is considerably less expensive provided the user carefully chooses the segment numbering and matrix bandwidth according to the guidelines discussed in the user documentation.

The user specifies the quantities to be computed from the wire currents, such as impedances, coupling parameters, and near field and/or far fields. These are computed from currents regardless of the solution process specified. In any case it must be emphasized that the user must be familiar with general results from the literature to insure that the computed solution using the model for the system is of sufficient accuracy for the purposes intended. For example, the far fields can be computed from approximate currents obtained by specifying a weak convergence criterion when using the BMI solution method. This will allow the reduction of the required computer resources when large systems are being analyzed.

As mentioned earlier, the present code generates an interaction matrix from the MFIE and EFIE (Electric Field Integral Equation) discussed in the GEMACS engineering documentation. The wire current is represented by a sine, cosine, and pulse expansion function with redistribution at junctions based on the fractional length of each segment with respect to the total length of all segments connected at the junction. The surface current is represented by pulse function. The interaction matrix may be modified by loading the individual segments or patches of the model using resistance, capacitance, and inductance in parallel or series configurations.

Associated with the geometric structure and interaction matrix is an excitation matrix which contains the total tangential electric field present at the midpoint of each segment or patch. The electric field may be caused by as many combinations of three types of sources as desired. These types are plane and spherical wave sources for scattering problems and voltage sources for antenna problems. In addition, the user may assign an arbitrary value to the excitation of any wire segment to force the desired boundary condition.

With the interaction matrix denoted by [Z] and the excitation matrix denoted by [E], the primary function of the code is to generate and solve the system of equations for the electric current [I]:

$$[Z]\,[I] = [E]$$

This may be done using direct full matrix decomposition if the structure is electrically small.

For electrically large problems, the direct solution method may be prohibitive due to the large amount of time required and the possible roundoff errors. In this case, the BMI (Banded Matrix Iteration) technique is available. When using BMI, the user must provide the convergence measure and value to be used to stop the iterative procedure. Three criteria or measures are available: the BCRE (Boundary Condition Relative Error), the IRE (Iterative Relative Error), and the PRE (Predicted Relative Error).

Once the solution has been obtained, the input impedance of each voltage driven element (i.e., Antenna Feed Point) is output to the user. These are computed simply as

$$Z_a = \frac{V_a}{I_a}$$

since a delta-gap model is used for antenna sources. The currents may also be used as inputs to the field computation routines to obtain the near- and/or far-electric field patterns, and the coupling between pairs of antennas.

There are inherent limitations to the solution techniques available. The user who is not familiar with these techniques is advised to consult the engineering manual and its references in order to not waste valuable time and computer resources working an ill-posed problem.

It should also be understood that certain limitations and assumptions exist in GEMACS with respect to wire grid modeling. These are shown in Figure 1. Regarding geometries that are modeled as wire screen approximations to the actual surface, the currents in the model exist only on the axis of the wires in the grid, whereas physically they are spread over the entire area of the surface.

It follows then that since the current exists only on the axis of the wire, there is no azimuthal variation of the current around the circumference of the wire, as would exist physically on the antennas.

Also because of the assumed concentration of the current on the axis of the wires there is no radial component of current flow within the wire. This has significance in the generation of near-field phenomena at the ends of the wire.

Antenna sources are generally modeled as a delta voltage source placed across a subsection. This may have no counterpart whatsoever in the physical situation. Moreover, the size of the gap in the model usually does not bear any relation to the size of the gap in the physical antenna. The gap in the model is usually the same size as the length of the adjacent subsections, since one of the modeling rules of thumb is to avoid large ratios in the relative lengths of adjacent subsections.

The current on a subsection is computed at the center of the segment and the variation over the wire is determined by interpolation between adjacent centers.

Even though all these assumptions are built into a GEMACS analysis, or a MOM analysis in general, good correlation exists between measured data and predicted data, and between other analytical results and the data obtained by using GEMACS.

All the commonly used codes assume that the material of which the system is composed is perfectly conducting. Brute-force techniques can be used to get around this limitation, but they place a heavy burden on the user. Alternate solutions are being pursued and will be included in future versions of GEMACS.

Finally, the MOM wire grid model can be used only to solve the external problem. Problems that cannot be treated with confidence include coupling through apertures in the skin of the structure and coupling between antennas located on opposite sides of the structure. Since the structure is modeled by a wire grid, electromagnetic energy will "leak through" the mesh in the model, thus resulting in a form of aperture coupling. For the antenna coupling problem, energy will go directly through the body in addition to going around on the surface. Thus, the coupling will be greater than if the surface were modeled as a solid. The solid surface model has been implemented into the GEMACS code to eliminate some of these present limitations.

The GEMACS inputs are in two categories. The command language directs the program execution while the geometry language is used to describe the geometrical properties of the structure being analyzed.

The GEMACS command language is a free-field, keyword-oriented input stream. The order of the inputs is generally not important, and the items on each card are delimited by a blank or a comma. An item is considered to be all of the input associated with a particular parameter. An item may consist of several entries where each entry is referred to as a field. Blanks may be imbedded between fields of an item but not within a field.

The command language essentially consists of a description of the electrical environment of the structure including the effect of loads, external or incident fields, voltage-driven or antenna source segments, ground parameters, frequency, selection of the matrix equation solution technique, and additional commands which permit intermediate calculations to be performed, stored (checkpointed), resumed (restarted), or purged. In addition, processing time limits, upper limit to the number of processing files required, and checkpoint timing control are specified at this input level.

The GEMACS geometry language is also a free-field language. However, the items must appear in the order specified or an error will occur which may not be detected. The reason for not using keyword-specified items on the geometry inputs is to decrease the effort required by the user since the geometry inputs are usually much larger than the command inputs.

The basic elements of GEMACS are points and line segments. These in turn may belong to larger data groups with a given name. Any reference to this given name will also reference all the points and segments within that group. In addition, line segments may also be identified as a group by having the same tag number.

The subsection may thus be identified by either a segment number or a tag number. The difference is that the first is unique in the model while the second may be shared by any number (or all) of the subsections within the geometry model.

The geometry data set is the basic source of data for many other GEMACS commands. It must be available before an impedance, excitation, load, or output data set can be generated. Additionally, the accuracy of the results is extremely dependent on the applicability of the structure representation for the analysis being performed.

As mentioned above, GEMACS employs both external and internal excitation of structures. The external excitation includes both spherical and plane elliptically polarized waves. The internal excitation is specified as a voltage applied to a wire segment. This voltage is converted to an electric field at the segment midpoint using the delta gap excitation. All segments driven by a voltage source are considered as antenna sources and as such will have the power and impedance of the segment computed after the structure currents have been obtained. Multiple sources will be superimposed if they are at the same frequency.

The structure may be loaded with series or parallel combinations of resistors, inductors, and capacitors. All load commands are cumulative for the same resultant or load data sets for a given frequency. The power dissipated in all loads will be displayed after the structure currents have been obtained.

Once the electrical environment has been established, the solution for the electrical currents flowing on the structure at the frequency specified may be obtained.

There are three types of output provided by GEMACS: the standard boiler-plate, those data specifically requested by the user; and error messages and debug information needed by the user when a problem exists during implementation of the computer code.

After the electrical currents have been obtained, the GEMACS code recovers the geometry, load, and source data associated with the currents. It will then compute the impedance, admittance, and power for all voltage driven (antenna source) and loaded elements. Unless specifically directed, no other output will occur. Additional output is obtained by using print, write, and field data commands.

Specialized print and write commands may be used to obtain a list of the currents on the structure as well as the contents of any data set. A print command lists the entire contents of a data set, while a write command lists those data specifically requested by the user. The latter could be used to print out a limited set of elements of the interaction matrix if the currents appear questionable to the user, for example.

The field data command will result in the computation of the near or far electric fields. The output will list the vector components of the field and optionally plot the magnitudes as directed. The near field will be determined for Cartesian, cylindrical, or spherical coordinates. The use of spherical coordinates with the radius parameter omitted will result in the far field being computed. This is the only mechanism to control near and far field output.

The data are preceded by an informative message giving the symbol name, the links to other symbols, and the data type. Since these data are complex, the real and imaginary magnitude and phase are given for the current (amperes) and the excitation (volts/meter) on each segment. (Ref. RADC-TR-77-137, Vol. 1, p. 94).

The plots provided with the current release of GEMACS serve to show qualitatively the nature of the beam pattern. They can be useful for quickly detecting anomalies, deep nulls, or unexpected shifts in the direction of the main beam. The axes are unlabeled and the references depend on the most rapidly varying coordinate and the coordinate system being utilized.

The optional graphic display is controlled by a six-choice item on command. If this item is defaulted, then only a tabular listing of the data will be output by GEMACS. If one of the six choices is present, then the plot will be in either a rectangular or polar form with axes in either a linear or logarithmic progression. Each of the six choices is made up of two merged mnemonics as follows:

1. LINLIN - Both the dependent and independent variables are plotted linearly on a rectangular graph.

2. LINLOG - The independent variable is plotted linearly and the dependent variable is plotted logarithmically on a rectangular graph.

3. LOGLIN - The independent variable is plotted logarithmically and the dependent variable is plotted linearly on a rectangular graph.

4. LOGLOG - Both the independent and dependent variables are plotted logarithmically on a rectangular graph.

5. LINPLR - The independent variable is plotted as a function of angle from the reference, and the dependent variable is plotted linearly on a polar graph.

6. LOGPLR - The independent variable is plotted as a function of angle from the reference, and the dependent variable is plotted logarithmically on a polar graph.

In each of these plots the independent variable will be one of the geometric variables: X,Y,Z in the Cartesian coordinate system; R,θ, Z in the cylindrical coordinate system; and R,θ,ϕ in the spherical coordinate system. Also the coupling between pairs of antennas may be obtained from the data output by GEMACS. The coupling may be obtained by calculating:

$$10 \log_{10} \left(\frac{\text{Power Dissipated in Load}}{\text{Power Input}}\right).$$

GEMACS is structured to write a checkpoint at specified time intervals, on command, or on detection of a fatal error during execution of any command. In order to recover from a checkpoint, a restart command has been provided. The restart action is straightforward; on encountering the restart command in the input stream, all previous input is overwritten with the contents of the checkpoint file.

There is an extensive set of messages available to the user that is printed when GEMACS encounters an error during input processing or during

the performance of an analysis. These are automatically printed out without the need for a user request.

If the error should occur during the execution of the analysis, GEMACS will terminate the analysis at that point, print out an appropriate error message and take a checkpoint, if a checkpoint command has appeared in the command stream prior to the command that initiated the operation in which the error occurred. Since there is a checkpoint file available, it is possible to restart from the command at which the error occurred once the source of the error has been located and corrected.

If an error is found during the reading of the input deck, GEMACS will print the appropriate error message and continue processing the rest of the input cards. If subsequent errors are found, further error messages are printed. However, execution of the analysis process will not be initiated. GEMACS will terminate after the input processing has been completed, and it will print out the contents of the input deck with the error message immediately following an improper command.

A walkback feature is also incorporated which lists the subroutine calling sequence from the subroutine which detected the error to the main routine within GEMACS.

In addition to the error messages a wealth of information is available regarding actual processing that occurs during execution. These data can be obtained through the use of debug commands. Statistics may also be collected and output which describe what subroutines were accessed, how often, the amount of Central Processing Unit (CPU) time expended in each subroutine and the percentage of the total CPU time spent in each subroutine.

GEMACS has been and is currently being applied to a number of major systems. One major system that the program has been used for is the Blackhawk Helicopter.

2.3 Software Considerations

GEMACS is written in American Standard FORTRAN, X 3.9-1966 and consists of approximately 20,000 lines of code. It is capable of executing with no library subroutines other than those required by the ANSI standard. The code requires approximately 95K decimal core locations (depending on machine and load method utilized) and may be segmented or overlayed. As released, neither of these features is utilized due to incompatibility with various machines.

Although no system library routines are required, some are desirable. The most important is a routine to return the elapsed CPU time in minutes. Such a routine must be available for effective use of the checkpoint command.

Auxiliary routines to return the date and time are called by an internal subroutine. In the absence of these routines, zeros should be returned to the calling routine.

The file status function routine is called after each READ to detect an end of file. If a library function is available to determine this information, it should be called from this routine. If none is available, a zero value for the function should be returned.

Regarding input/output requirements, GEMACS makes extensive use of peripheral file storage and must have several logical units available. The user is responsible for assuring that GEMACS can access these files whose data sets consist of geometry, excitation, impedance, banded results, decomposed matrix results, current, and field data. If more files are required than made available, a fatal error will occur and an attempt will be made to write a checkpoint. To this end, a final GEMACS resource requirement is the presence of a checkpoint file.

A functional breakdown of the GEMACS structure is shown in Figure 2. The GEMACS executive routines control the interface of the code with the host computer and perform three basic functions: input/output to peripheral files, taking checkpoints and restarting from these checkpoints, and the compilation of statistical information, which can be used to pinpoint areas for further code refinement.

The input language, task execution and run termination processors simply read the user's data deck, call appropriate subprocessors based on the user's commands and terminate the analysis, respectively. Within these two upper levels in Figure 2 are all of the file handling capabilities built into GEMACS. With a proper interface for the new subprocessors under the task execution processor, these new subprocessors can change the field analysis technique or even apply the mainframe to a different type of problem completely, such as the dynamic load analysis of some structure.

The geometry processor generates the geometry to be analyzed by interpreting the user geometry input commands. The interaction matrix processor generates the elements of the interaction matrix for the frequency and geometry specified by the user. The excitation processor generates the elements of the vector on the right-hand side of the MOM matrix equation. The load processor modifies the interaction matrix to take into account the presence of loads on the wires or the presence of imperfectly conducting materials. The matrix solution processor solves the MOM matrix equation for the currents on the structure. The output processor calculates such quantities as the near and far-field patterns and terminal impedance for antennas or the backscattering from the structure. The direct manipulation processor sets such variables as the maximum CPU time allowed for the analysis, the number of files in the system available to the code, the frequency of the analysis and the electrical characteristics of the ground (if present). It also performs arithmetic operations, such as modifying the frequency by some factor, a feature which is useful when "looping" is inserted into the command stream.

This modular construction of GEMACS has its advantages. First, and most obvious, is that one can plug in any technique which has a proper interface or driver to transfer data between the implementing subroutine and the mainframe. It is therefore possible to have a complete set of techniques stored in separate files. The big difference is that

communication with all these techniques is in one common language. There is no need for the user to be familiar with several different sets of input formats, or limit himself to one specialized code.

Secondly, and highly significant, is the fact that GEMACS is tied into the Air Force Intrasystem Analysis Program (IAP). This means that it will have the full support of the Air Force to provide aid in the loading, use and maintenance of the code, additions to the capability of the code, updates to eliminate any bugs that may be in the code, and support a common language among all users of the code.

The problem-handling capabilities of GEMACS are limited by the computer resources available to the user. As presently dimensioned, GEMACS can accommodate up to 20,000 wire segments. Generally, MOM analyses have been limited to relatively small systems i.e. those that can be represented by 300 subsections or less. Electrically, this latter size corresponds to a size of approximately 30 wavelengths of wires or a surface with an area of one square wavelength. This has not been due to a limitation of the theory or the technique, but has been brought about by the computer resources needed to perform a MOM analysis; however, the range of applicability of the moments technique is extended to objects of larger electrical size in GEMACS through use of the BMI solution method. In terms of wavelengths, an electrically large system is one which has an area of at least 10 square wavelenths for a plane surface, or one which has a linear dimension of at least 200 wavelengths for a single dimension system. The future development and inclusion of other analysis methods and techniques will further increase the frequency analysis capability of the program for a given object size and complexity.

Execution times on the Honeywell 6180 computer system for a typical system consisting of a variable number of subsections are shown below. These figures represent analysis times (CPU seconds) using the full matrix solution meth ; as a function of the number of segments.

#Segments vs. Full Matrix Solution Time

110 segments	255.24 sec.*
305 segments	2876.04 sec.
500 segments	10076.76 sec.

*Note: These numbers are computer-system dependen'. In this regard, the Honeywell system is relatively slow.

GEMACS has been installed on the following major computer systems:

CDC/CDC CYBER
IBM
UNIVAC
PDP
BURROUGHS
HONEYWELL
VAX

2.4 Source

The GEMACS program was developed and written by the BDM Corporation, Albuquerque, NM for Rome Air Development Center (RADC/RBCT), Griffiss Air Force Base, NY. It was approved for public release circa 1977. The program is currently maintained by the IIT Research EMC/IAP Support Center, Griffiss Air Force Base, NY. The program and related services can be obtained directly from the Support Center whose total GEMACS user community to date consists of the following agencies which represent government, industry, and academia:

ADTC/ADDSU
AEROJET ELECTRO SYSTEMS
AEROSPACE CORPORATION
APPLIED TECHNOLOGY
AUBURN UNIVERSITY
AVCO SYSTEMS DIVISION
BBC BROWN BOVERI & COMPANY LTD
BELL AEROSPACE TEXTRON
BOEING COMPANY
CONTROL DATA CORPORATION
DEFENCE RESEARCH ESTABLISHMENT
DEPT OF COMMERCE
E-SYSTEMS INC
EATON CORPORATION
ECAC/IITRI
GENERAL DYNAMICS
GENERAL DYNAMICS CORPORATION
GEORGIA INSTITUTE OF TECHNOLOGY
HARRIS CORPORATION
HONEYWELL INC
IIT RESEARCH INSTITUTE
JET PROPULSION LAB
LOCKHEED MISSILE & SPACE COMPANY
DIGITAL EQUIPMENT CORPORATION
GEC-MARCONI ELECTRONICS LTD
GENERAL MOTORS INSTITUTE
GTE SYLVANIA
HOKUTO TRADING COMPANY
IBM CORPORATION
IITRI/ECAC
JOHN DEERE
MARTIN MARIETTA AEROSPACE
MCDONNELL DOUGLAS CORPORATION

NAVAL AIR SYSTEMS COMMAND
NAVAL RESEARCH LAB
NORTHROP CORPORATION
R C HANSEN INC
RADC/RBCT
RAYCHEM CORPORATION
RCA ASTRO ELECTRONICS
ROCKWELL INTERNATIONAL
ROYAL AUSTRALIAN AF
SANDERS ASSOCIATES
SANDIA LABORATORIES
SPERRY UNIVAC
SRI INTERNATIONAL
TEXAS INSTRUMENTS
UNIVERSITY OF KENTUCKY
US ARMY CORADCOM
USACEEIA/CCC-EMEO-EDC
WESTINGHOUSE ELECTRIC CORPORATION
WSMC-SEM

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Thomas R. Ferguson, Theodore H. Lehman, and Robert J. Balestri, "Efficient Solution of Large Moments Problems: Theory and Small Problem Results," IEEE Transactions on Antennas and Propagation, March 1976, pp. 230-235.

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ACTUAL GEOMETRY REPRESENTED BY THIN WIRES

CURRENT EXISTS ONLY ON WIRE AXIS

NO AZIMUTHAL VARIATION OF CURRENT

NO RADIAL COMPONENT OF CURRENT

ANTENNA SOURCES ARE GAP MODELS

CURRENTS DETERMINED ONLY AT POINTS

SYSTEM LIMITED IN SIZE

PERFECT CONDUCTORS

EXTERNAL PROBLEMS

MOM ASSUMPTIONS & LIMITATIONS
(WIRE GEOMETRY MODELING)

FIGURE 2

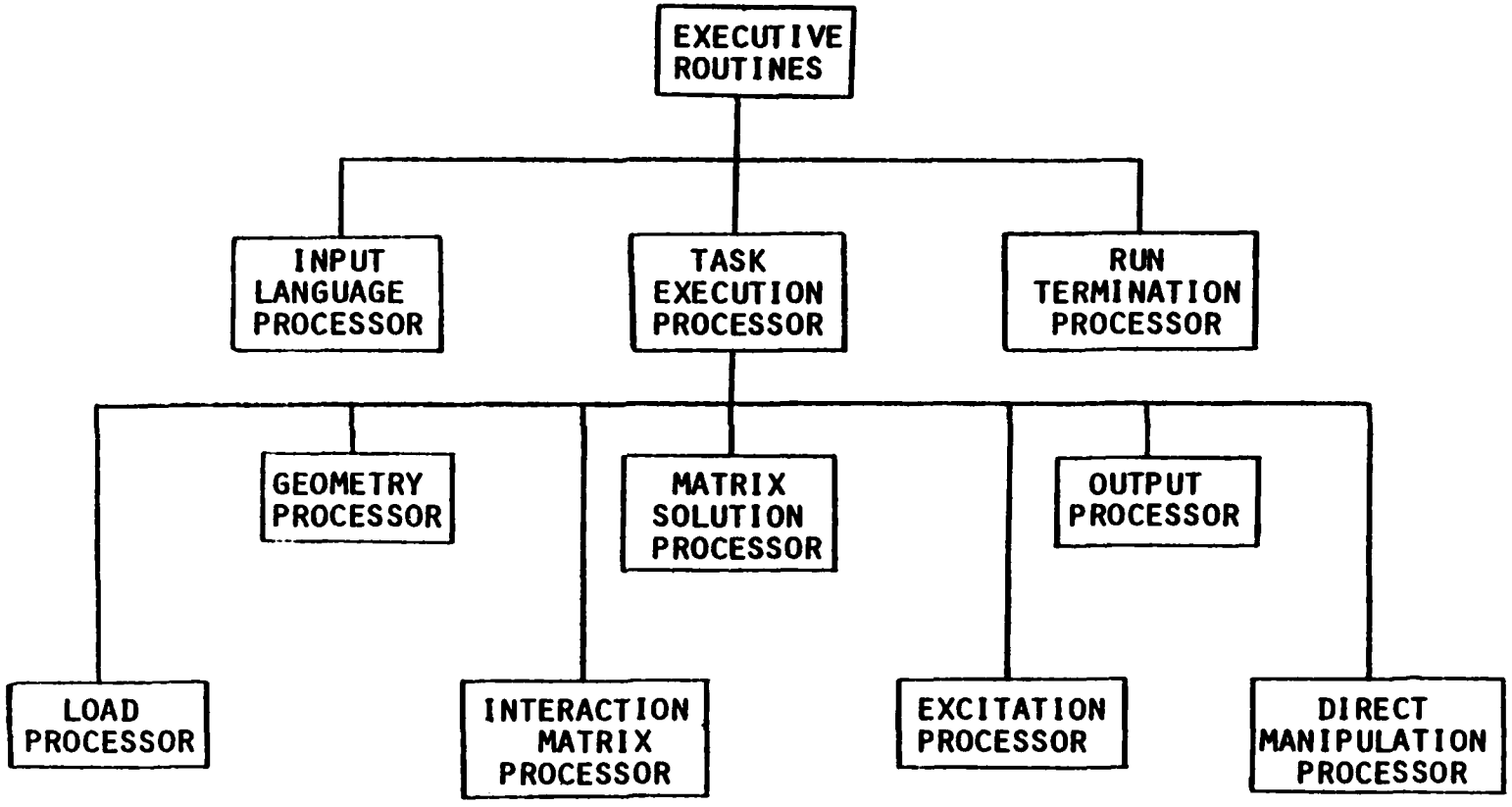

FIGURE 3 GEMACS STRUCTURE

SECTION 3.

NONLINEAR CIRCUIT ANALYSIS PROGRAM

(NCAP)

3. Nonlinear Circuit Analysis Program (NCAP)*

3.1 Introduction

NCAP is an acronym for the Nonlinear Circuit Analysis Program. It is a user-oriented computer code for determining the nonlinear transfer functions of weakly nonlinear electronic circuits. By utilizing a standard set of circuit elements, NCAP can analyze networks made up of interconnections of these elements.

Structurally, NCAP solves the nonlinear network problem by forming both the nodal admittance matrix (Y matrix) for the entire network, and the first-order generator (current-source) excitation vector, for each of the linear sources in the entire network. The generators can be located between any node in the network, and can have any desired frequency, amplitude and phase. Using Gaussian elimination with the admittance matrix and the current vector, results in the first-order nodal voltage vector for the network, whose elements are the first-order transfer functions at all nodes in the network at the given excitation frequency. When there is more than one generator at a given frequency, the first-order transfer function will be the total transfer function due to the superposition of the generators since the first-order transfer function is a linear function. The higher-order transfer functions are solved in an iterative fashion using techniques which are described in more detail below.

NCAP is relatively simple to employ. The user enters a description of the circuit to be analyzed; NCAP interprets the input statements, performs the nonlinear analysis, and outputs the results in printed form. There are several types of input statements which are needed to analyze a given circuit. The input statements define the topology of the circuit, the circuit element values, the linear and nonlinear devices used in the circuit, the circuit excitation and the order of the analysis, the desired output, the data modification and sweeping descriptions.

3.2 Code Description and Capabilities

The purpose of NCAP is to provide the EMC analyst and system designer with a technique for solving weakly nonlinear EMC problems which often present themselves in varying degrees of complexity. NCAP, under the general framework of the Air Force Intrasystem Analysis Program (IAP), could be applied after a more coarse analysis has indicated a potential EMC problem at the circuit level. At this point NCAP could be used to examine in more detail, the nonlinear effects which are often encountered in practice which can severely degrade system performance. It can be shown that many important nonlinear interference effects such as desensitization intermodulation, and cross modulation can be specified in terms of the nonlinear transfer functions, computed by NCAP. A knowledge of the magnitude of these effects could be very valuable in the early stages of system design.

*The discussion which follows is extracted directly from the documents entitled: Nonlinear Circuit Analysis Program (NCAP) Documentation, RADC-TR-79-245, Volumes I-III.

NCAP employs the Volterra analysis technique (a weakly nonlinear series approximation) to compute the nonlinear transfer functions of electronic circuits. From the point of view of the user, the NCAP system is composed of three elements: an input language, through which the user describes the circuit to be analyzed, a computational phase which solves the network problem on a nodal basis, and an output phase which prints and/or plots the desired results (plotting algorithms currently under development). The user is only required to be able to translate a circuit analysis problem into the appropriate NCAP input language statements. By means of this "language" one describes the circuit to be analyzed, the frequencies and order of analysis and the desired output. In turn, the system interprets these input statements, performs the nonlinear analysis and outputs the results in printed or plotted form.

NCAP uses a set of standard electronic circuit element models, and can analyze networks made up of interconnections of these elements.

The following circuit elements have been included in the NCAP model:

- Independent Voltage Source
- Linear Dependent Sources
- Nonlinear Dependent Sources
- Linear Components
- Nonlinear Components
- Vacuum Diode
- Vacuum Pentode
- Semiconductor Diode
- Bipolar Junction Transistor
- Field Effect Transistor

Since the NCAP analysis is performed on a nodal basis, the first step in the analysis of a circuit should include a schematic of its complete circuit model. This diagram should include all of the NCAP elements which can be identified and modeled.

The nonlinear transfer functions computed by NCAP are voltage transfer ratios which relate an output response voltage to one or more input excitation voltages. Therefore, in order to determine a nonlinear transfer function, it is necessary to define the parameters of the input signals of the circuit and the frequencies at which the analysis is to be performed.

In NCAP these input signals are considered to be generated by independent sinusoidal voltage sources. Voltage sources (generators) can be connected between any two nodes in the circuit, and a single source can generate an arbitrary number of frequencies.

The order of analysis which the program will carry out is equal to the total number of defined frequencies in the circuit with the nonlinear transfer functions computed for all $2^n - 1$ possible combinations of n input frequencies.

The output of a typical NCAP run, printed on the computer's line printer, can consist of a large volume of information. In general the

output consists of images of all input cards, all circuit devices with their associated parameters values, and all scaled nonlinear transfer functions and node voltages. The transfer functions and node voltages are printed for each node and each order for every possible frequency combination, in both Cartesian and log-polar form.

In the event that errors are detected in the input deck, the printout of the erroneous input card will be followed by an error message describing the type of error encountered. Once such an error has been found, processing of the input deck will continue until the last card is read. At this point, execution of the program will terminate and the output will consist of only the input card images and appropriate error messages.

The successful analysis of a large circuit can result in an inordinately large amount of printed output; therefore, several output control statements have been included in the NCAP language to allow the user to specify the desired output and to reduce the amount of printout obtained.

A number of optional features have been incorporated in the NCAP system to increase its versatility and ease-of-use. For example, in order to provide the user with a method of analyzing circuits over a range of frequencies or linear component values, an incremental sweep capability has been included in the NCAP program. This feature enables the user to specify numerous analyses for a given circuit in a single computer run. The basic circuit description, together with all sweep definitions, are input only once. The system then automatically re-analyzes the circuit for all possible frequency and component values.

A modify feature, which allows the user to alter nonlinear device parameters and re-analyze a circuit in a single computer run, has also been incorporated in NCAP. Such modification may also be applied to frequency and component values, either to change the parameters of a previously defined sweep, or to define additional values which may lie outside the range of a sweep.

A recent application of NCAP involved the prediction of Radio Frequency Interference (RFI) to the 741 operational amplifier which was subjected to multiple signal inputs. NCAP was successfully used to predict undesired, low-frequency responses in the OP-AMP caused by demodulation of amplitude modulated (AM) RF signals in the range of .05 MHz to 100 MHz.

3.3 Software Considerations

NCAP is written in ANSI Standard Fortran IV and can analyze networks containing up to approximately 500 nodes. Although the program is large and its analytical technique complex, the modular structure, adherence to naming conventions for subprograms and variables, and numerous in-line comments allow NCAP to be readily adapted to any computer with an appropriate Fortran compiler. Sparse matrix routines are used to decrease core storage requirements and increase computational efficiency of the program.

The program consists of eight phases, numbered 0 through 7. Each phase performs a distinct portion of the circuit analysis and operates independently of the other phases. The only interphase communication is by shared disk files: the Driver File, which is a translation of the NCAP input cards (denoted with asterisks) to a machine readable description of the circuit analyses to be performed, and the Data File, which contains all circuit element input data, calculated device parameters, admittance matrices, and transfer function vectors. Although several other disk files are used by NCAP, their function is to conserve core storage and to ease the transmission of internally generated data between the subprograms which comprise individual phases.

Phase 0 is the input processor for NCAP. It reads and interprets the input deck mapping the input cards to appropriate driver and data file records. Phase 1 calculates the device parameters for each circuit element, collects and tabulates the circuit's frequencies, and determines the size of the admittance matrices. Phase 2 constructs the admittance matrices, one for each possible combination of the circuit's frequencies. Phase 3 constructs the current vectors and calculates the transfer functions for each frequency combination. Phase 4 prints the results from the circuit analysis performed in Phases 1-3 and controls frequency sweeping. Phase 5 controls linear component sweeping, Phase 6 controls device modification, and Phase 7 controls generator modification.

Since numerous circuit analyses may be specified by a single NCAP input deck, the path of execution through the program phases is not necessarily sequential. Execution always begins at Phase 0 and proceeds sequentially through Phases 1-4 to perform the first circuit analysis. From Phase 4, program execution either reverts back to Phase 1 to initiate a new analysis if frequency sweeping is specified, or proceeds to Phase 5 if frequency sweeping is not specified or after all such sweeps have been satisfied. In a similar fashion, Phases 5, 6, and 7 may either cycle back to Phase 1 or proceed to the next phase depending on the linear component sweeping, device modification, and generator modifications specified in the input deck. Program execution ends with Phase 7 after the last (if any) generator modification has been effected.

Each phase is composed of a principle subprogram which controls its general operation, a group of secondary subprograms which perform specific operations for individual circuit elements or NCAP functions, and in some cases, additional support subprograms which perform operations unique to that phase. The program is organized sequentially according to the order of the phases. Within each phase, the principle subprogram appears first,

followed by the secondary and support subprograms in alphabetical order. A group of shared support subprograms, such as those which perform disk input/output or complex arithmetic, follow Phase 7 and appear in alphabetical order.

The principle subprograms of each phase are subroutines, with the exception of Phase 0 whose principle, in order to satisfy the requirements of Fortran, is NCAP's main program. These principle subroutines are named PHASE0, PHASE1,...,PHASE7. With the exception of two function subprograms, the remainder of the NCAP subprograms are subroutines.

Wherever possible, the subprograms are named according to specific conventions. Subprograms which perform specific functions related to circuit elements are prefixed or suffixed with a device identifier:

GEN	= Generator
JFET (or JF)	= Junction Field Effect Transistor
LC	= Linear Components
LDS	= Linear Dependent Source
NC	= Nonlinear Components
NDS	= Nonlinear Dependent Source
PT	= Vacuum Pentode
SD	= Semiconductor Diode
T (or TRN)	= Bipolar Junction Transistor
VD	= Vacuum Diode
VT	= Vacuum Triode

Furthermore, within each phase the secondary subprogram names contain functional identifiers:

IN	= Read and interpret input cards
CP	= Calculate parameters
MT	= Create matrix elements
CUR	= Calculate current elements

Together, the device and functional identifier describe the purpose of the subprogram; GENIN = input generator card sequence, CPPT = calculate pentode parameters, MTT = create transistor matrix elements, CPMTVD = calculate parameters and create matrix elements for vacuum diode, CURNDS = calculate current elements for nonlinear dependent sources.

At the support level, subprograms which perform complex arithmetic are prefixed by CX (CXADD, CXDIV, etc.), while disk I/O routines are suffixed by RD and WR (DATARD,DRIVWR, etc.). Support subprograms whose functions are too specific to be categorized are named as descriptively as possible; LOCTF = locate transfer function, FRPRM = create frequency permutation.

The program code for subroutines PHASE1 through PHASE7 are all organized in a similar manner. Execution through these routines is controlled by reading and processing the driver file records sequentially. Each driver record contains a functional identifier or mode, which serves as the index of a computed "GO TO", selecting the proper code segment to process that record. The coding for each driver function is arranged numerically by mode within the subroutine and begins with the statement number equal to the value of the mode. Additional statement numbers within a code segment are assigned in increments of 100. For example, a section of transistor code would begin with statement 9 (the transistor driver mode), and proceed through 109, 209, 309, and so on.

In a similar fashion, the IN family of subroutines (input card processors) share a common organization. Execution through these subroutines is based on a computed "GO TO" using the card type identifier as an index. The coding for each card type is arranged numerically within the subroutines and statement numbers are allocated in increments of 100 within code segments.

The narrative descriptions of the NCAP subprograms which follow are arranged in the order in which they appear in the program: by phases and within phases and by alphabetical order. Each subprogram description contains a brief statement of purpose, followed by a variables list, subroutines called, calling programs, and a detailed narrative of the program code. Wherever possible mathematical algorithms are summarized and where possible tables of all possible computed results are presented.

To avoid repetition, variables which are used globally within the program are listed only in the Phase 0 description or in the first principle subprogram in which they are used. In the secondary and support subprogram descriptions, only local variables (or in some cases less frequently used global variables) are listed.

Machine-dependent code is clearly identified in both the program listing and narrative descriptions in order to ease the adaptation of NCAP to various computer systems.

Typical execution times based upon implementation on the Honeywell 6180 series computer are shown below. These figures are in terms of Central Processing Unit (CPU) seconds and refer to typical sample cases which exercise the various models and specialized analysis features. The number of nodes per model and order of analysis has also been indicated below:

Typical Execution Times

Analysis Task	#Nodes	Order	CPU Time (sec.)
FREQUENCY SWEEPING	4	3	33.84
COMPONENT SWEEPING	3	2	9.0
DEVICE MODEL MODIFICATION	26	3	63.36
IMPEDANCE MODIFICATION	4	3	15.48

The program requires approximately 51K decimal words of core storage (on the Honeywell 6180 computer) and consists of 10,475 lines of Fortran code. The program has successfully been installed on the following computer systems:

CDC/CDC CYBER
IBM
UNIVAC
HONEYWELL
PDP
VAX

3.4 Source

The Rome Air Development Center (RADC) has been tasked with the development of analysis techniques for weapon system electromagnetic compatibility (EMC) assurance. This development effort is formally known as the Air Force Intrasystem Analysis Program (IAP). The IAP concept, initiated within the Air Force in the early 1970's, presently consists of a collection of computer-aided analysis routines for addressing various aspects of intrasystem EMC. The analysis routines range in applicability from an overall system (aircraft, satellite, etc). level EMC model to detailed wire coupling and circuit analysis models (NCAP). The program is currently maintained by the IIT Research Institute, EMC/IAP Support Center, Griffiss Air Force Base, New York. The program and related services can be obtained directly from the Support Center whose total user community to date consists of the following agencies which represent government, industry, and academia:

ADTC/ADDSU
AEROSPACE CORP
BBC BROWN BOVERI AND CO. LTD.
BOEING COMPANY
DEPT OF COMMERCE
ECAC/IITRI
GEC-MARCONI ELECTRONICS LTD.
GENERAL DYNAMICS

GENERAL DYNAMICS CORP.
GEORGIA INSTITUTE OF TECH.
HOKUTO TRADING CO. INC.
HUGHES AIRCRAFT CO.
IIT RESEARCH INSTITUTE
LOCKHEED MISSILE & SPACE CO.
DEFENSE ELECTRONICS RESEARCH
DIGITAL EQUIPMENT CORP.
IBM CORPORATION
JOHN DEERE
MARTIN MARIETTA AEROSPACE
MCDONNELL DOUGLAS CORP.
NAVAL AIR SYSTEMS COMMAND
NAVAL AIR TEST CENTER
NAVAL RESEARCH LAB
PURDUE UNIVERSITY
RCA CORP.
ROCKWELL INTERNATIONAL
ROCKWELL INTERNATIONAL CORP.
SANDERS ASSOCIATES
WESTINGHOUSE ELECTRIC

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SECTION 4.

WIRE COUPLING PREDICTION MODELS

4. Wire Coupling Prediction Models*

4.1 Introduction

Coupled transmission lines have continually received much attention in many diverse areas of application. Multiconductor transmission lines (MTL) have been investigated in early power system studies and continue to receive attention in this area with regard to the transient behavior of power lines under fault and lightning induced conditions. Modern emphasis on multilayer distributed circuits, strip lines and microstrip associated with integrated-circuit technology has produced a renewal of interest as has the interest in predicting transients induced on cables by external electromagnetic field sources such as high-power radars or an electromagnetic pulse (EMP) from nuclear detonations. Determining cross-talk in communication circuits and digital computer wiring interference are examples of other areas in which the subject of multiconductor transmission lines consistently arise.

Of particular interest within the electromagnetic compatibility (EMC) community is the prediction of coupling between wires and their associated termination-networks in closely-coupled, high-density cable bundles and flat pack (ribbon) cables on modern electronic systems.

In the case of wire-to-wire coupled interference in cable bundles, undesired coupling of energy between circuits sharing a common bundle may be more severe than one may realize. For example, numerous cases (both experimental and analytical) may be shown where, for certain frequencies, the ratio of the received interference voltage across the terminals of a device to the voltage emitted by another device, which is coupled via wire-to-wire coupling mechanisms, exceeds unity. The two devices are not directly connected by a common pair of wires; the wires connected to each device are only in close proximity in a common cable bundle.

The computer programs described herein are intended to provide a supplement to the analysis capabilities of the Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP) by providing a more fine-grained analysis of wire-coupled interference. They implement the multiconductor Transmission Line (MTL) model.

IEMCAP is intended to be used to model all recognizable coupling paths on aircraft, ground and spacecraft systems. By virtue of the large size and complexity of many of these systems, detailed modeling of the coupling paths is not feasible in a program such as IEMCAP. To avoid excessive computer run times, the models of the various coupling paths used in IEMCAP are generally quite simple and represent bounds on the coupling. Consequently, the predictions of IEMCAP are generally somewhat conservative. However, once a potential wire-coupled interference problem is pinpointed by IEMCAP, the computer programs described above can, in many cases, be used to determine if an actual interference situation exists and the precise level of the interference.

* The discussions below were extracted directly from the documents entitled: Applications of Multiconductor Transmission Line Theory to the Prediction of Cable Coupling, RADC-TR-76-101, Volumns I - VIII.

Shielded cables have also been used extensively on aircraft, ground and space-missile systems to reduce the crosstalk between electrical equipments which are interconnected by wires. The wires which interconnect these electrical and electronic devices are generally routed in densely-packed, cable bundles. The unintentional electromagnetic coupling or crosstalk between these wires may be of sufficient magnitude to degrade the performance of the equipments which the wires interconnect. In order to reduce this level of crosstalk, shielded cables and twisted pairs of wires have been employed.

The Wire Coupling Prediction Models discussed herein are based on a complete and unified consideration of multiconductor transmission line theory as it applies to the prediction of wire-coupled interference. In addition to considering the limitations and advantages of the analysis and predition techniques, some numerically stable and efficient techniques for solving the multiconductor transmission line problem for large numbers of closely-coupled, dielectric-insulated wires are included. Methods for computing the per-unit-length parameters are also taken into account.

The various coupling models place emphasis on the frequency response of the transmission lines rather than on the transient response since EMC control documents currently apply predominantly to the frequency domain. If one assumes linear termination networks (no hysteresis, etc.) and assumes no nonlinear effects associated with the transmission lines such as corona discharge, then the equations describing the problem (the transmission lines and associated terminations) will be linear and thus the frequency response provides a completely general characterization.

Matrix formulation of the equations and other results of matrix analysis are applied where necessary for a logical and concise development.

The Wire Coupling Prediction Model software tools consist of seven separate codes: XTALK, XTALK2, FLATPAK, FLATPAK2, GETCAP, WIRE, and SHIELD.

Although XTALK, XTALK2, FLATPAK, and FLATPAK2 implement the MTL model, each one considers or neglects certain factors such as conductor losses in order to provide an efficient computational program. XTALK neglects the presence of any wire dielectric, i.e., considers the wires to be bare, and also neglects the conductor losses, i.e., the conductors are considered to be perfect conductors. XTALK2 also neglects the presence of wire insulation but includes conductor losses. FLATPAK includes consideration of wire dielectrics as in ribbon cables but considers the conductors to be lossless. FLATPAK2 includes consideration of wire dielectrics and also includes the conductor losses. XTALK2 requires more array storage and computation time than XTALK. FLATPAK2 requires more array storage and computation time than FLATPAK. Similarly, FLATPAK requires more computation difficulty than XTALK. Therefore rather than writing one general MTL program to consider all factors, four programs, each of which are efficient for the specific problem being investigated are established. Note that none of the programs consider insulation dielectric losses. This seems to be a reasonable assumption and its validity has been determined by comparing the program results to experimental results.

The digital computer program GETCAP (which is an acronym for GEneralized and Transmission line CAPacitance matrices) is a Fortran code which calculates the per-unit-length generalized and transmission line capacitance matrices for ribbon cables for the analysis of crosstalk.

The problem of determining the currents induced in termination networks at the ends of a multiconductor transmission line by an incident electromagnetic field is obviously quite important in determining the electromagnetic compatibility of electronic systems. The digital computer program WIRE is designed to calculate the sinusoidal steady-state terminal currents induced at the ends of a uniform, multiconductor transmission line which is illuminated by an incident electromagnetic (EM) field.

In order to assess the effectiveness of preventative measures involving cable shielding it is desirable to have prediction models which characterize this coupling. The analysis and prediction tool SHIELD addresses this. SHIELD also predicts the coupling effects due to pigtails which can seriously degrade the effectiveness of braided-shielded cables.

It is, of course, difficult if not impossible to write a general computer program which would address all types of transmission line structures which the user may wish to investigate. The programs discussed form an initial library of specialized analysis capabilities for wire-coupled interference problems.

4.2 Code Description and Capabilities

XTALK

XTALK considers (n + 1) conductor transmission lines consisting of n wires in a lossless, homogeneous surrounding medium and a reference conductor for the line voltages. The n wires and the reference conductor are considered to be perfect (lossless) conductors. There are three choices for the reference conductor type:

- The reference conductor is a wire.
- The reference conductor is an infinite ground plane.
- The reference conductor is an overall cylindrical shield which is filled with a homogeneous dielectric.

XTALK2

XTALK2 analyzes the same three structural configurations as XTALK except that the conductors are considered to be imperfect.

FLATPAK

FLATPAK analyzes (n+1) wire ribbon cables. All wires are assumed to be perfect conductors.

FLATPAK2

FLATPAK2 analyzes the same configuration as FLATPAK except that the wires are considered to be imperfect conductors.

In all of the above programs, the medium surrounding the conductors is assumed to be lossless. Sinusoidal, steady-state excitation of the line is considered, i.e., the transient solution is not directly obtained.

The above programs consider the line cross-sectional dimensions as well as conductor impedance via the per-unit-length impedance and admittance matrices which take into account mutual and self-interactions. These basic parameter matrices are used in determining the terminal voltages and currents.

The equations used in the programs for the entries in the per-unit-length transmission line matrices in XTALK and XTALK2 are valid for "large" conductor separations. Generally, this means that the smallest ratio of wire separation to wire radius should be no smaller than approximately five (5). The exact values for these matrices for ribbon cables are computed by GETCAP and used in FLATPAK and FLATPAK2.

The per-unit-length inductance matrix is computed in XTALK and XTALK2 using the "large conductor separation approximations" described above. The per-unit-length capacitance matrix is then determined from the inverse of the per-unit-length inductance matrix since the surrounding medium is assumed to be homogeneous. Terminal voltages are determined using either the Norton Equivalent representation of the terminal networks or the Thevenin Equivalent representation.

The per-unit-length transmission line matrix entries for XTALK2 analysis follows from the developments provided in XTALK taking into account the lossy properties of the conductors.

In the case of program FLATPAK, the relationship between the per-unit-length inductance and capacitance matrices used in XTALK and XTALK2 no longer holds since the surrounding medium about each conductor is assumed to be inhomogeneous. FLATPAK addresses the specific problem of transmission lines consisting of perfect conductors in a lossless, inhomogeneous medium. For example, dielectric insulations surrounding wires result in an inhomogeneous medium (dielectric insulation and the surrounding free space).

By virtue of the permeability characteristic of the surrounding medium, the surrounding medium is considered to be homogeneous; therefore, evaluating the per-unit-length capacitance matrix with the wire dielectric insulations removed is necessary. Hence, one needs to compute the per-unit-length capacitance matrix with and without the wire dielectric insulations present. The GETCAP code was written to compute these per-unit-length capacitance matrices of ribbon cables which can be used as inputs to FLATPAK.

FLATPAK2 uses the per-unit-length capacitance and inductance matrices computed by GETCAP assuming perfect conductors as in FLATPAK. The self impedances of the wires are assumed identical since the wires in the ribbon cable are typically indentical. The per-unit-length impedance and

admittance matrices are appropriately modified to account for the lossy nature of conductors.

All input data are supplied through cards (card images). All four of the programs require three groups of data input:

- o Transmission Line Structure Characteristics (Group I)
- o Termination Network Characterization (Group II)
- o Frequency Data (Group III)

The data entries are either in Integer (I) format or Exponential (E) format and must be right-justified in assigned card column blocks.

In all four programs, the user must appropriately dimension all arrays for each problem. Comment cards are provided at the beginning of each program to assist the user in providing proper dimensions.

Each frequency card contains one and only one frequency for which an analysis is desired. More than one frequency card may be included in the frequency card group. Each program will process the data provided by Groups I and II and compute the response at the frequency on the first frequency card. It will then recompute the response at each frequency on the remaining frequency cards. The program assumes that the data on card Groups I and II are to be used for all the remaining frequencies. If this is not intended by the user, then one may run the program for one frequency at a time. This feature, however, can be quite useful. If the termination networks are purely resistive, i.e., frequency independent, then one may use as many frequency cards as desired in this frequency card group and the program will compute the response of the line at each frequency without the necessity for the user to input the data in Groups I and II for each additional frequency. Many of the time-consuming calculations which are independent of frequency need to be computed only once so that this mode of useage will save considerable computation time when the response at many frequencies is desired. If, however, the termination network characteristics (Group II) are complex (which implies frequency dependence), one must run the program for only one frequency at a time.

The termination network characterization data conveys the terminal characteristics of the termination networks at each end of the line. The termination networks are characterized by either the Thevenin Equivalent or the Norton Equivalent. The impedance or admittance matrices in these characterizations of the terminations may either be "full" in which all entries are not necessarily zero or may be diagonal in which only the entries on the main diagonal are not necessarily zero and the off-diagonal entries are zero. The user may select one of four options for communicating the entries in the vectors and matrices for both ends of a line. These are:

- o Thevenin Equivalent representation; diagonal impedance matrices

- o Thevenin Equivalent representation; full impedance matrices
- o Norton Equivalent representation; diagonal admittance matrices
- o Norton Equivalent representation; full admittance matrices

Each of the matrix entries is, in general, complex, i.e., real and imaginary data inputs are required.

Group I data generally consists of specifications of the number of wires, (relative) dielectric constant of surrounding medium, (relative) permeability of surrounding medium, transmission line length, wire radii, interior radius of shield (reference conductor is an overall cylindrical shield), and any relevent rectangular or angular coordinates which describe the wire system geometry and orientation. When the reference conductor is a wire, an arbitrary rectangular coordinate system is established with origin at the center of the reference conductor. The radii of all wires as well as the rectangular (y,z) coordinates of each wire serve to completely describe the structure. When the reference conductor is an infinite ground plane, the arbitrary coordinate system is established with the ground plane as the z axis. The y coordinates define displacements relative to the ground plane. Finally, for the cylindrical shield as the reference conductor, an arbitrary angular coordinate system is established with the origin of the coordinate system at the center of the shield. The radii of the wires and their angular and radial positions are described relative to the coordinate system origin.

The outputs for the above programs generally consist of predictions of the terminal voltage for each wire (with respect to the reference conductor) at the ends of each wire. The magnitudes and angles of these induced voltages represent the degree of crosstalk within the system.

The prediction of crosstalk in ribbon cables was investigated. Based on the experimental configurations tested, accurate predictions of crosstalk were achieved in controlled characteristic cables such as those discussed above. The prediction accuracies are typically within $\pm$ 1dB for frequencies such that the line is electrically short ($1\ell.1\lambda$).

In summary, the four digital computer programs, XTALK,XTALK2, FLATPAK, and FLATPAK2 are used in determining the electromagnetic coupling within an (n+1) conductor, uniform transmission line. Sinusoidal steady-state behavior of the line as well as the Transverse Electromagnetic (TEM) or "quasi-TEM" mode of propagation are assumed.

General termination networks are provided at the ends of the line and the programs compute the voltages (with respect to the reference conductor) at the terminals of these termination networks.

GETCAP

The GETCAP code was developed to characterize a system of wires as a multiconductor transmission line which can be used to predict crosstalk in

ribbon cables. These general techniques employed in FLATPAK and FLATPAK2 require that the per-unit-length transmission line capacitance and inductance matrices of the system be determined. GETCAP determines these matrices.

Approximations to the elements of the transmission line capacitance matrix can be obtained for cases with no dielectric insulation, providing the separation between the conductors is at least ten times the conductor radius which in turn can be used to develop an approximate expression for the transmission line inductance matrix. An approximate method of determing the transmission line capacitance matrix for bare conductors above an infinite ground plane has been postulated where the smallest ratio of conductor separation to wire radius must be greater than ten. In this case, one can assume that the per-unit-length charge on each conductor surface is uniformly distributed around the conductor periphery.

Ribbon cables, however, have a much smaller conductor separation than is required for these approximations to be valid, and in addition have dielectric insulations. It has been shown, in fact, that the approximate formulas based on constant charge distributions are no longer sufficiently valid for close spacing and dielectric material surrounding the conductors.

Ribbon cables have been used for many years in computer bus connections. They are recently finding greater usage in other types of systems such as aircraft and missiles. In these applications, the various conductors connect electronic devices at either end of the cable. Of considerable importance when using these cables is the ability to predict interference or crosstalk. Crosstalk can result in possible bit errors in computer signals and the mixing of signals in analog systems. The ability to compute the transmission line capacitance matrix for such cables enables the multiconductor transmission line equations to be solved. This in turn will enable a more precise analysis of ribbon cable systems through a detailed analysis of crosstalk.

GETCAP is a method for computing the capacitance matrix for dielectric-coated conductors as applied to the case of ribbon cables. Simplifications in the method were made possible by the symmetry of the cable dimensions; the radii of the conductors are all identical, and the center-to-center spacing of adjacent wires is identical. In addition, the wires are oriented in a horizontal plane which is maintained throughout the length of the cable. A method was incorporated to optimize the selection of matchpoint techniques to ensure valid results and reduce computation time.

From the generalized capacitance matrix, the transmission line capacitance and inductance matrices are output; these matrices are used in frequency response and crosstalk analyses of cable systems using FLATPAK and FLATPAK2. An approximate method for determining the transmission line inductance matrix was also incorporated.

The problem to be solved is described by the following variables:

- The number of wires in the cable.

- o The radii of the conductors.
- o The radii of the outer dielectric insulation surfaces.
- o The center-to-center separation of any two adjacent conductors.
- o The relative dielectric constant of the insulation material (relative to free space).
- o The total number of Fourier series terms to be used to represent the charge distributions around the conductor surfaces and the dielectric surfaces.
- o The reference conductor for the transmission line voltages.
- o A program option selector which allows for
    - o Matrix partitioning to invert the charge distribution matrix.
    - o Standard full inversion of the charge distribution matrix.
    - o Inversions involving removal of dielectrics (bare wire cable).

The aforementioned variables are grouped into three user-oriented data categories: 1) problem description cards, 2) physical characteristics cards, and 3) an option card. Inputs are in Integer (I) or Exponential (E) format and are input in prescribed card columns (right-justified).

Typical output from GETCAP consists of the header page, followed by the input data as defined (errors are flagged when encountered). The generalized and transmission line capacitance matrices with regard to the reference conductor for the line voltages is then output.

WIRE

The digital computer program, WIRE, is designed to compute the sinusoidal, steady-state terminal currents induced in a multiconductor transmission line by a single-frequency, incident electromagnetic field. The transmission line consists of n wires (cylindrical conductors) and a reference conductor. The reference conductor may be a wire, an infinite ground plane or an overall, cylindrical shield. All (n+1) conductors are assumed to be perfect conductors and the surrounding medium is assumed to be linear, isotropic, homogeneous and lossless. The line is assumed to be uniform in that all (n+1) conductors have no variation in their cross-sections along the line length and are parallel to each other.

Two types of incident field specifications are provided for. Uniform plane wave excitation can be specified for the wire and infinite ground plane reference structures whereas nonuniform field excitation can be specified for all structure types.

The primary restrictions on the program validity is that the cross-sectional dimensions of the line, e.g., wire spacings, must be electrically small and the smallest ratio of wire separation to wire radius must be larger than approximately 5.

General linear termination networks are provided for at the two ends of the line. All input data are specified on cards (card images). All of the programs require three groups of data input:

Transmission Line Structure Characteristics (Group I)
Termination Network Characterization (Group II)
Field Specification (Group III)

The data entries are either in Integer (I) format, or in Exponential (E) format. All data entries must be right-justified in the assigned card column block. These data entries are printed out by the program.

In the program, the user must appropriately dimension all arrays for each problem. Comment cards are provided at the beginning of the program to assist the user in providing proper dimensions.

The input data categories above are very similar to those requirements specified for the XTALK, XTALK2, FLATPAK, and FLATPAK2 codes. The only exception is with regard to the field specification.

For uniform plane wave illumination of the line, the format of the input data consists of two groups. Group #1 consists of one card containing the magnitude of the electric field intensity vector, Em, the angle between this vector and the projection of the y-axis on the plane containing the electric field (this plane is perpendicular to the propagation direction), the angle between the y-axis and the direction of propagation, and the angle between the z-axis and the projection of the propagation vector onto the x,z plane. The x coordinate is parallel to the n wires and reference conductor, and the y,z plane forms the cross-section of the line. The origin of the coordinate system, is fixed by the user according to the specification in Group I. The zero phase of the incident wave is taken at the origin of this coordinate system.

Card Group #2 consists of an unlimited number of cards with each frequency of the incident wave on each card. More than one frequency may be included in this frequency card group. The program will process the data provided by Groups I and II and the wave orientation data in Group #1 and compute the response at the frequency on the first frequency card. It will then recompute the response at each frequency on the remaining frequency cards. The analysis technique per frequency is based on the same philosophy as was discussed for programs XTALK, XTALK2, FLATPAK, and FLATPAK2.

For non-uniform field illumination, Group #1 consists of one and only one card which contains the frequency of the field.

The remaining cards contain the values of the longitudinal electric field (magnitude and phase) along the n wires (and reference) which are directed in the +x direction, and the transverse electric field along

straight line contours joining the i-th wire and the reference conductor at x=0 and x=ℓ i.e. transmission line endpoints. The directions of the transverse field at these specification points are tangent to the contours and directed from the reference conductor to the i-th wire.

The output data generally consists of basic header information, a summary of the system parameters modeled, followed by a summary of the magnitudes and phases of the terminal currents (per frequency) induced by the environmental field.

SHIELD

The SHIELD code is a prediction model for accurate simulation of crosstalk to or from braided-shield cables employing transmission line theory.

Two main problems are addressed by the SHIELD code. These include the effect of pigtails on braided-shield cables which result when cables are terminated in connectors and can lead to significant degradation in the effectiveness of a shield in the reduction of crosstalk and the prediction of crosstalk between braided-shield cables.

The distributed parameter, multiconductor transmission line equations are solved for steady-state, sinusoidal excitation of the line. The line consists of unshielded and shielded wires where the wires may be above a ground plane or within an overall, cylindrical shield. Furthermore, the impedances of all conductors are incorporated within the model. The shielded wires may have solid or braided shields (through-braid coupling for braided shields is also included in the coupling prediction model).

Historically, during the development of SHIELD for coupling prediction and analysis, two coupling models were considered. A low-frequency model was valid only for a "sufficiently small" frequency. The upper limit to this frequency range was not unique but depended on the load impedances and physical configuration. However, the simplicity of this model allowed considerable insight into the coupling phenomenon. For the purposes of providing this qualitative insight and obtaining approximate predictions, this model served a useful role.

The multiconductor transmission line (MTL) model required considerably more computational effort, and the qualitative features of the coupling which were transparent in the low-frequency model were obscured in the MTL model. The advantage of the MTL model is its prediction accuracy. With the MTL model, one need not be concerned about the limitation of the frequency being sufficiently small as was required for the low-frequency model. The prediction accuracies of the MTL model tended to be in the range of 1dB-3dB when the line is electrically short and 6dB - 10dB when the line is electrically long.

In addition, certain effects which were of a distributed nature which were not predictable with the low-frequency model were accurately predicted with the MTL model. For example, in the case of a single-end grounded shield and high impedance loads, there was a considerable difference in crosstalk depending on which end of the shield was grounded.

Clearly, this is a distributed effect not predictable by the low-frequency model. However, the MTL model predicted this result within a few dB.

In addition to specifying the number of shielded and unshielded wires involved, the following types of input data are necessary and are restricted by specific card column formats:

- o Shielded/Unshielded wire data
  - o Transmission line length.
  - o Indication of reference conductor (including height above ground or distance from center of shield).
  - o Wire radii.
  - o Number of wire strands and corresponding radii.
  - o Conductivity of strands (relative to copper).
  - o Rectangular coordinate location (relative to ground) or angular position (shield reference).
  - o Interior shield radius.
  - o Relative permitivity of interior dielectric (shielded wires).
- o Specialized shield characteristics
  - o Shield thickness.
  - o Shield conductivity (relative to copper).
  - o Radius of braid wires.
  - o Braid wire conductivity (relative to copper).
  - o Braid wire angle.
  - o Number of belts in braid.
  - o Number of wires per belt.
- o Pigtail characteristics (left and right sides)
  - o Length of pigtail.
  - o Radial separation of pigtail wire from shielded wire.
  - o Angular position of pigtail wire.
  - o Radius of pigtail wire.

- o Number of strands in pigtail wire.
- o Radius of pigtail wire strands.
- o Conductivity of pigtail wire strands (relative to copper).

- o Terminal source and impedance data (shielded and unshielded wires)
  - o Real and imaginary components of current source between wire and reference conductor at the endpoints of the transmission line.
  - o Real and imaginary components of admittance between wire and reference conductor and between each wire at the endpoints of the transmission line.

The voltages between each wire and the reference conductor are calculated at discrete frequencies.

An added complication results during the use of random cable bundles which are groups of wires (cylindrical conductors) whose relative wire positions are unknown and vary in some uncontrolled fashion along the cable length. These cable bundles result from the need to contain wires connecting electronic equipments in compact groups. Current practice in the avionics industry is to group wires into these random bundles although the use of ribbon cables (in which wire position is carefully controlled) is increasing. These random bundles can be quite large and no attempt is made to control the relative wire positions within the bundle.

The seemingly obvious approach to interference analysis is the use of uniform, multiconductor transmission line theory to model the cable bundle. However, this model requires that the wires be parallel to each other along the entire cable length and their relative positions, of course, must be known and should not vary along the cable length. Random cable bundles do not satisfy these criteria. Another difficulty inherent in the application of the MTL model is the computation time required to obtain the response at each frequency. Determining the response of a large number of closely coupled wires at a large number of frequencies can be quite time consuming even on a modern, high-speed digital computer. Furthermore, in cases where the cable responses are sensitive to variations in relative wire position, it may be impossible to obtain predictions with any extreme degree of accuracy in random cable bundles. A more reasonable approach would seem to be the use of simpler models which bound or at least estimate these, perhaps sensitive, cable responses.

4.3 Software Considerations

The contents and general operation of the codes are discussed below. With the exception of program GETCAP, all other Wire Coupling Prediction Model codes require the use of supplemental software. These will be discussed accordingly.

All programs conform to ANSI Standard Fortran IV and were originally written in double-precision arithmetic. However, these codes have been converted to single-precision arithmetic. All the programs were originally implemented on an IBM 370/165 computer at the University of Kentucky using the Fortran IV, G-level compiler and are easily implemented on other computer systems.

The programs and required supplemental software, approximate number of lines of Fortran code, and required core storage are summarized below:

Program	Required Subroutines	Core Requirements* (Decimal words)	Program Size (#Source lines)
XTALK	LEQT1C	17K	368
XTALK2	LEQT1C, EIGCC	19K	534
FLATPAK	LEQTIC, NROOT, EIGEN	17K	474
FLATPAK2	LEQT1C, EIGCC	17K	429
GETCAP	---	15K	932
WIRE	LEQTIC	20K	703
SHIELD	LEQTIC, EIGCC	30K	1629

*Figures are based upon implementation on Honeywell 6180 Computer System.

The required supplemental routines are part of the IMSL (International Mathematical and Statistical Library) package which may be replaced by other appropriate general purpose routines. These are briefly discussed below in terms of function.

Subroutine LEQT1C

Subroutine LEQT1C is a general subroutine for solving a system of n simultaneous, complex equations.

Subroutine EIGCC

Subroutine EIGCC is used to find the eigenvalues and eigenvectors of an n x n complex matrix.

Subroutines NROOT and EIGEN

Subroutines NROOT and EIGEN are a set of subroutines which compute the eigenvectors and eigenvalues of a matrix product. (These were a part of the IBM Scientific Subroutine Package (SSP).)

The typical execution times above are based on sample test cases which involve anywhere from two to five wires. The programs were designed to operate in as little time as possible, using as little duplicated storage as possible. Run times can be significantly reduced by running the programs on optimized Fortran compilers, e.g. levels G or H, using an object code; object code no longer requires a compilation stage, thus overall execution time can be improved. Problem size limitations are dependant primarily upon internal array sizes within each program which may be modified to expand the analysis capability; also, available computer resources should be considered when modeling large systems. Execution time, of course, will be dependant on the problem size and in general, increases with the consideration of additional wires.

Programs GETCAP, WIRE, and SHIELD require the use of additional internal functions and subroutines above and beyond those discussed above in order to perform their specialized analyses. Those additional functions are described below.

The entire GETCAP program consists of five program units:

MAIN------The main program for inputting data and controlling output of results.

GETCAP----The subroutine which performs the actual computation of the capacitance matrices from the input data.

MINV------A matrix inversion subroutine from the IBM Scientific Subroutine Package (SSP).

MPC-------A subroutine which multiplies two general matrices, then multiplies the resulting matrix by a constant.

MPRT------A subroutine which outputs a general matrix to the printer in matrix format with labeling.

The WIRE code is comprised of three program units:

MAIN------The main program which controls the flow of input data, provides excutive control over all operations, and is responsible for ouput of results.

E1--------A function subprogram which evaluates (in closed form) integrals analogous to Fourier Transforms in direct, complex algebraic form.

E2--------A supplementary function subprogram which evaluates integrals similar to the type solved by subprogram E1.

Program SHIELD consists of the following subprogram units:

MAIN------The main program which reads the input data, coordinates the execution of the analysis, and controls the data output.

LS1-------Function for computing the self-inductance of conductors above ground.

LS2-------Function for computing the self-inductance of conductors in an overall shield.

LM2-------Function for computing the mutual inductances between conductors in an overall shield.

STB-------Function for computing the transfer elastances for braided shields.

LTB-------Function for computing the transfer inductances for braided shields.

ZWW-------Function for computing the self-impedances of stranded wires.

ZDB-------Function for computing the diffusion impedances of braided shields.

ZSB-------Function for computing the self-impedances of braided shields.

ZDS-------Function for computing the diffusion impedances of solid shields.

ZSS-------Function for computing the self-impedances of solid shields.

MULTC-----Subroutine which multiplies two complex matrices.

SCAP------Subroutine which computes the inverse of the capacitance matrix.

INDUCT----Subroutine for computing the inductance matrix.

PHI-------Subroutine for computing the chain parameter* matrices.

ADMADD----Subroutine for adding elastances to the inverse of the capacitance matrix.

IMPADD----Subroutine for adding impedances to the impedance matrix.

*used in the solution of transmission line equations where the chain parameter matrix (state transition matrix) generally represents first-order, complex-valued, ordinary differential equations which describe the transmission line for the TEM mode of propagation and the sinusoidal, steady-state conditions and are in the form of state variable equations.

For all the programs above the main program was written so as to be

used by non computer-specialists. The main program is an executive over its respective subroutines; it also checks the input data for obvious errors. The main program also provides the matrix and array storage areas used during the computations.

The Wire Coupling Prediction Models above have been implemented on the following computer systems:

CDC/CDC CYBER
IBM
PDP
DEC
VAX
UNIVAC
BURROUGHS
HONEYWELL

4.4 Source

The program development effort was conducted by the University of Kentucky under the sponsorship of the Rome Air Development Center Post-Doctoral Program for RADC's Compatibility Branch. The programs and associated user's documentation became available circa 1976 and is currently maintained by the IIT Research Institute EMC/IAP Support Center, Griffiss Air Force Base, NY.

The programs and associated products and services (in terms of program installation, modeling aid, etc.) can be obtained directly from the Support Center which is under RADC sponsorship.

A list of past and current users of the Wire Coupling Prediction Models is tabulated below:

ADTC/ADDSU
AEROJET ELECTRO SYSTEMS
AEROSPACE CORPORATION
BBC BROWN BOVERI & CO. LTD
BELDEN CORPORATION
BOEING COMPANY
DEFENSE ELECTRONICS RESEARCH
DIGITAL EQUIPMENT CORPORATION
EATON CORPORATION
GEC-MARCONI ELECTRONICS LTD
GENERAL DYNAMICS
GENERAL DYNAMICS CORPORATION
GTE SYLVANIA
HOKOTO TRADING CO. LTD
IBM CORPORATION
IIT RESEARCH INSTITUTE
LOCKHEED MISSILE & SPACE COMPANY
MARTIN MARIETTA
MCDONNELL DOUGLAS CORPORATION
NAVAL RESEARCH LABORATORY
RAYCHEM CORPORATION

ROCKWELL INTERNATIONAL
SANDERS ASSOCIATES
SPERRY UNIVAC
WESTINGHOUSE ELECTRIC

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